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Final Report

on

Contract No. AF33(616)-3386
Project No. 6-(1-3340)

Wright Air Development Center

W. L. Starkey, S. M. Marco, J. A. Collins

23 April 1958

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION

RF Project 674

Report No. 4

FINAL

REPORT

By

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION

COLUMBUS 10, OHIO

To Propeller Laboratory
Wright Air Development Center
Wright-Patterson Air Force Base, Ohio
Attention: WCLBA-1
Contract No. AF33(616)-3386
Task No. 33054
Project No. 6-(1-3346)

On AN INVESTIGATION OF THE MECHANISM OF THE FRETTING-CORROSION-FATIGUE PHENOMENON

For the period 1 February 1956 through 30 April 1958

Submitted by W. L. Starkey, S. M. Marco, and J. A. Collins

Date 23 April 1958

FOREWORD

This report was prepared by W. L. Starkey and J. A. Collins of The Ohio State University, Columbus 10, Ohio, on Air Force Contract No. AF33(616)-3386, under Ohio State University Research Foundation Project No. 674, "An Investigation of the Mechanism of the Fretting-Corrosion-Fatigue Phenomenon." The work was administered under the direction of the Propeller Laboratory, Wright Air Development Center, with Mr. Don Wian acting as project engineer.

ABSTRACT

The objective of this research program was to investigate the mechanism and consequences of the fretting fatigue phenomenon. The experimental program was designed to explore the effectiveness of shot-peening and cold-rolling on fretting fatigue damage, establish the Prot relationship for Ti-140-A titanium alloy, compare the endurance limits of two heats of titanium with the same nominal specifications, investigate fretting speed effects, perform microscopic studies of fretted specimens, and survey the literature in the field of fretting fatigue.

It was found that, while severe shot-peening is an effective fretting fatigue inhibitor, severe cold-rolling is a better way of inhibiting both fretting wear and fretting fatigue. It was found that the Prot method of endurance limit determination is valid for Ti-140-A titanium alloy. It was found that a significant difference in endurance limit existed between two heats of titanium with the same nominal composition. The speed of fretting has a pronounced effect on endurance limit. Many minute fatigue cracks were observed in the fretted area of a large number of specimens. The mechanism of fretting may be a combination of pit-digging and asperity-contact fatigue. Construction of a machine is proposed to study the phenomenon of fretting to determine which of the two mechanisms dominates under various conditions.

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

CONTENTS

AN INVESTIGATION OF THE MECHANISM OF
THE FRETTING-CORROSION-FATIGUE PHENOMENON

SECTION I.

INTRODUCTION

1.1 SCOPE OF REPORT

This report is the final technical report on Contract No. AF 33(616)-3386. The research program for this contract has been completed. All data collected on this research program are presented in tabular form in the Materials Data Section appended to this report. They are also presented graphically and are discussed in Section IV.

1.2 OBJECTIVES

The broad objectives of this research program were:

1. To investigate the mechanism and consequences of the fretting-corrosion-fatigue phenomenon.
2. To conduct experimental tests to define statistically the effects of certain combinations of variables in the fretting-corrosion-fatigue process.
3. To explore the mechanism whereby surface treatments such as shot-peening or cold-rolling tend to inhibit damage.
4. To explore the feasibility of using wire as a fretting-fatigue research tool.
5. To employ mathematical analysis, comprehensive literature survey, and experimental techniques to gain a better understanding of the basic mechanism of fretting fatigue.

1.3 BACKGROUND

A brief resume of the problems and conditions leading to this research program is presented in Appendix A of this report. This appendix also includes a summary of the research performed on the fretting problem prior to the beginning of the current program. It is suggested that, if the results presented in this report are to be fully understood, it would be advisable to read Appendix A before continuing with the remaining sections of this report.

1.4 MATERIALS DATA SECTION

Attached to this report, and designated as Appendix B, is a section entitled "Materials Data Section". This Materials Data Section is included in compliance with Part I of the Schedule to Contract No. AF 33(616)-3386. This section lists in tabular form all data accumulated on this contract.

SECTION II

DESCRIPTION OF EXPERIMENTAL APPARATUS

2.1 INTRODUCTION

Several pieces of experimental research equipment were used in carrying out this research program. Some of this equipment was modified commercially available equipment and some was specially designed and constructed as a part of the research project. The following paragraphs describe the major units of research equipment used in the experimental program.

2.2 SPECIMEN AND SHOE MEASUREMENT FACILITIES

To reproduce closely the fretting conditions from specimen to specimen, it was necessary to know and selectively control the size of the specimen and shoe at the fretting interface. It was found that accuracy in measurement of the order of 0.0001 inch was desirable on both specimens and shoes. To measure the specimens, a precision mechanical comparator with specimen positioning dowels and flexure plate measuring probe was constructed and coupled with a very accurate dial indicator to provide the necessary precision in measurement. This instrument is shown in Figure 2-1. The fretting shoes were measured with a self-centering probe type hole gage employing a precision dial indicator. This instrument is shown in Figure 2-2. Together, these two instruments provided the desired accuracy in measuring the fretting specimens and shoes.

2.3 SPECIMEN-FRETTING EQUIPMENT

A special fretting collet was used to produce fretting action on the surfaces of the test specimens. This collet, shown in Figures 2-2 and 2-3, was specially designed to be used with a standard Krouse 1500 in-lb. rotating beam fatigue-testing machine, replacing one of the original standard collets. With this special fretting collet in operation, the specimen was caused to press against the fretting shoes while the entire system of specimen, shoe, and collet rotated as a single member. This system, shown schematically in Figure 2-4, resulted in small amplitude cyclic relative motion between the shoe and the specimen because of differential strains of shoe and specimen as well as axial angularity of the specimen centerline with respect to the shoes. This mechanism was used to produce the fretting treatment on all titanium specimens used in the experimental program.

2.4 PROT FATIGUE-TESTING EQUIPMENT

Three 1500 in-lb. Krouse rotating-cantilever-beam fatigue-testing machines were used to perform all of the Prot endurance tests in this research program. A special Prot attachment consisting of a change gear box, flexible cable, and lead screw mechanism was incorporated into each Krouse rotating beam machine. This modification is shown schematically in Figure 2-5. With this modification the Krouse machines were capable of continuously increasing the stress at a constant rate per cycle. The rate at which the stress amplitude in the specimen is increased during each cycle is known as the Prot rate. A large variety of Prot rates was made available by the Prot attachment described above.

2.5 SHOT-PEENING EQUIPMENT

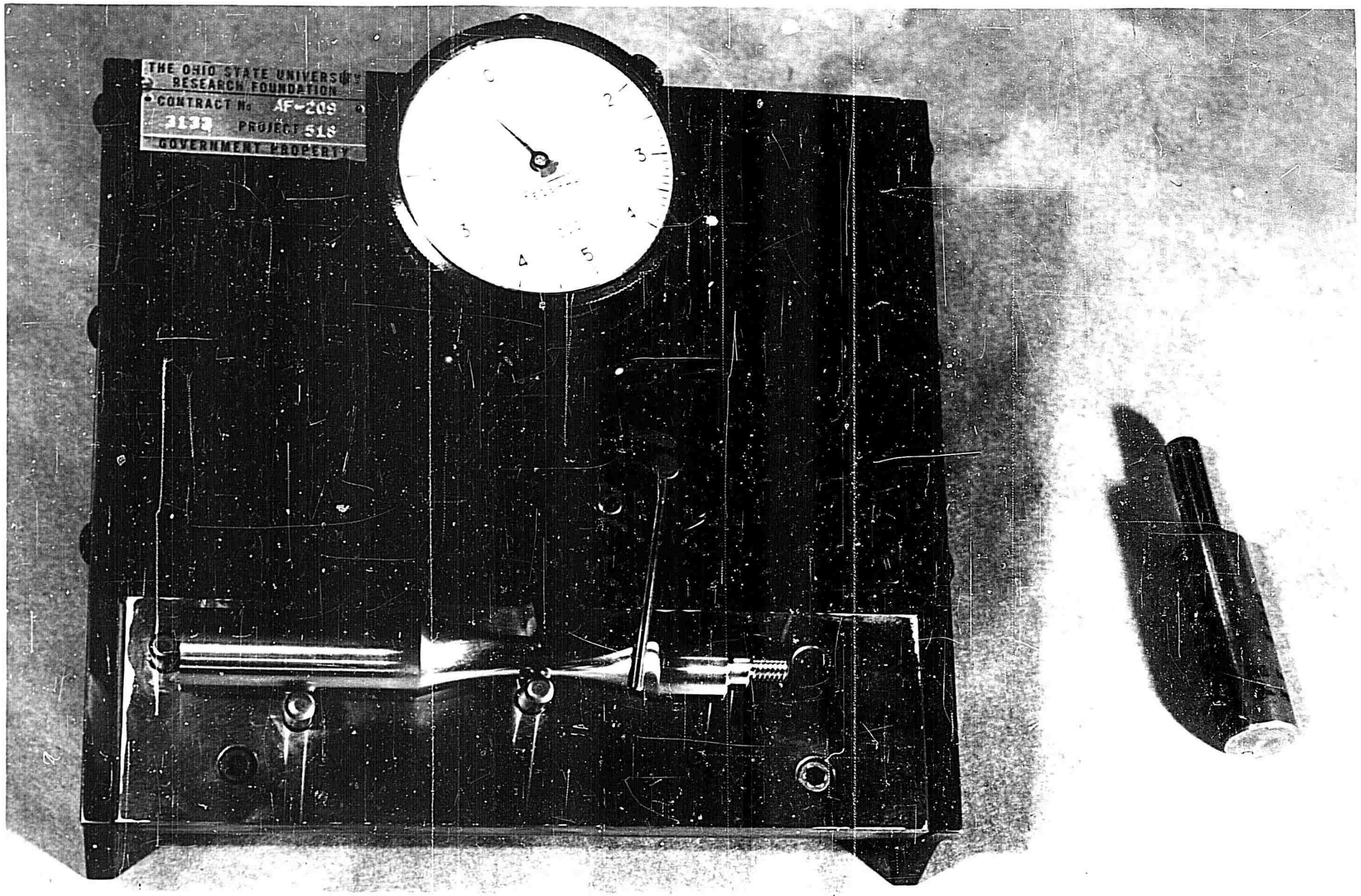
A commercially available shot-peening unit was purchased. To the basic unit were added a fixture to position and hold the blast nozzle, and a mechanism to rotate and translate the specimen through the shot blast. This specimen transport unit is shown in Figure 2-6. An overall view of the shot-peening facility is shown in Figure 2-7. All shot-peened specimens were prepared with this special shot-peening facility.

2.6 COLD-ROLLING EQUIPMENT

A special cold-rolling fixture to cold-roll the test sections of fatigue specimens was designed and constructed. As shown schematically in Figure 2-8, this fixture was basically a frame which spring-loaded three toroidal rollers against the test section of a fatigue specimen. Figure 2-9 is a photograph of this fixture. The cold-rolling apparatus was mounted on the saddle of a large lathe so that the specimen could be rotated between lathe centers while the cold-rolling fixture was translated by the lathe carriage. The load on the rollers was controlled by a calibrated spring. Extreme pressure lubricant was supplied to the specimen-roller contact area during the entire rolling process.

2.7 WIRE FATIGUE-TESTING MACHINES

Commercial wire fatigue-testing machines were used in the wire testing phase of the project. These machines, manufactured by the Krouse Testing Machine Company, used the principle of a rotating column to provide cyclic stresses in a wire. These wire fatigue-testing machines were used without modification.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PROJECT 518
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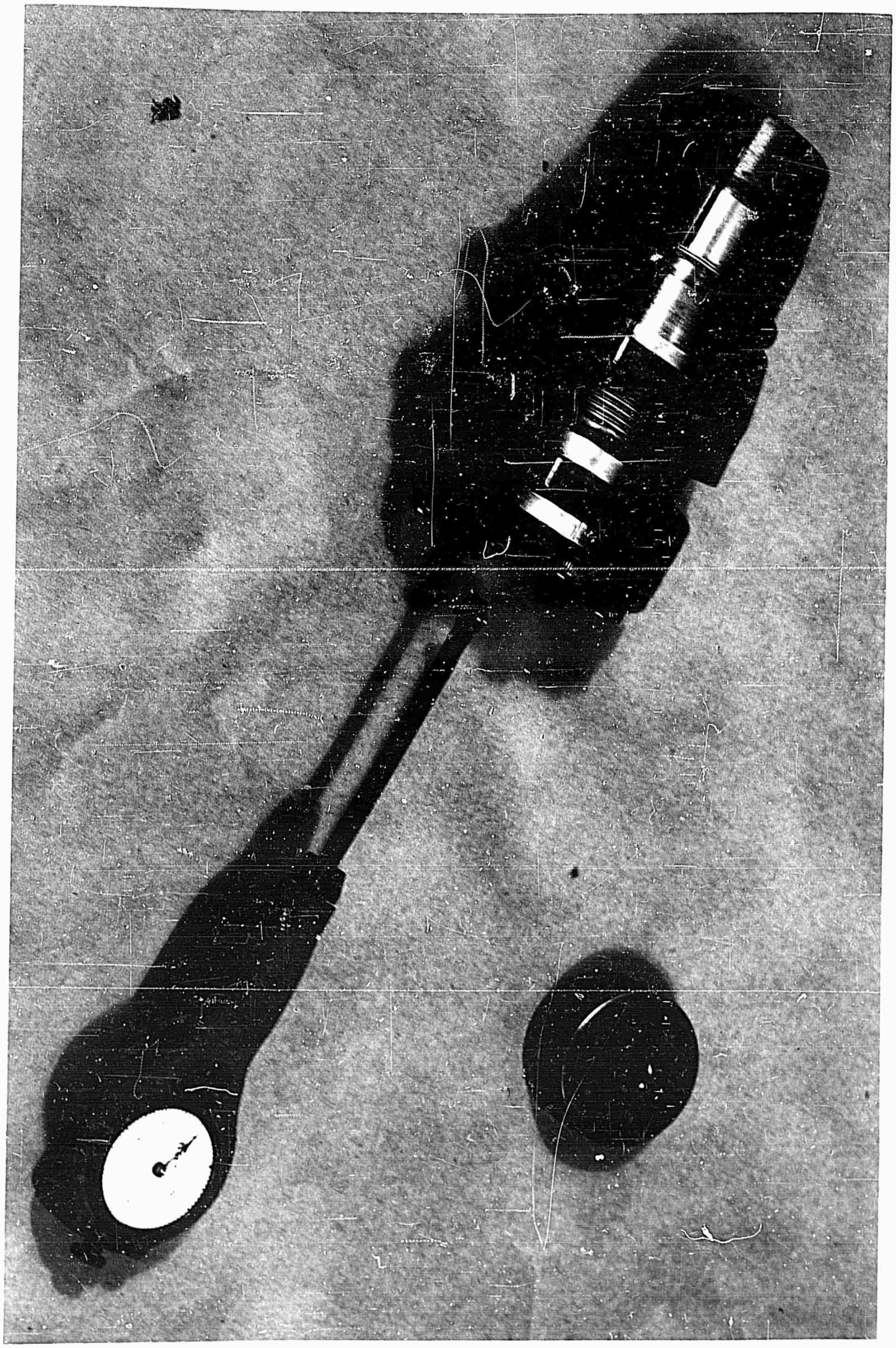

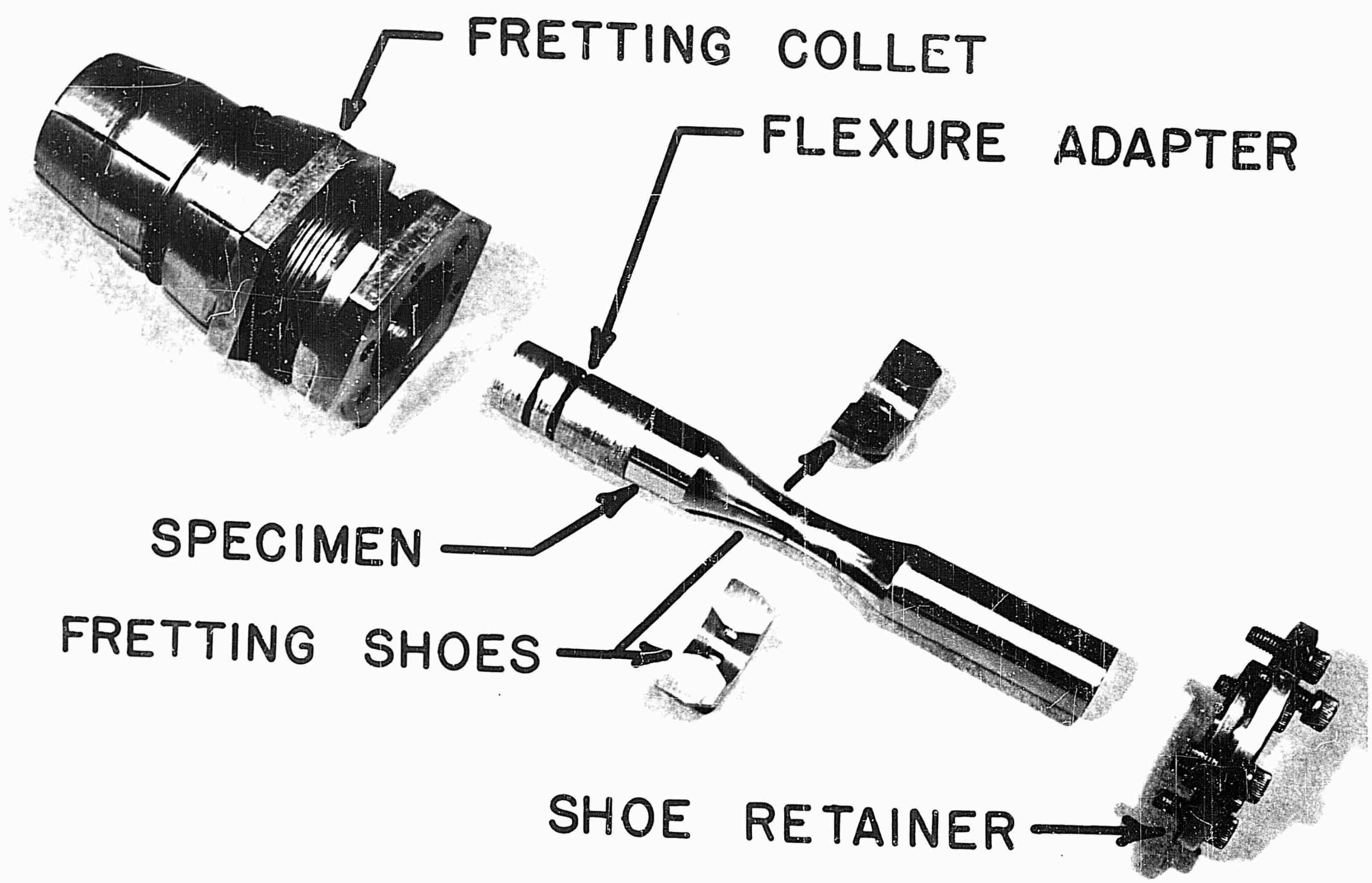
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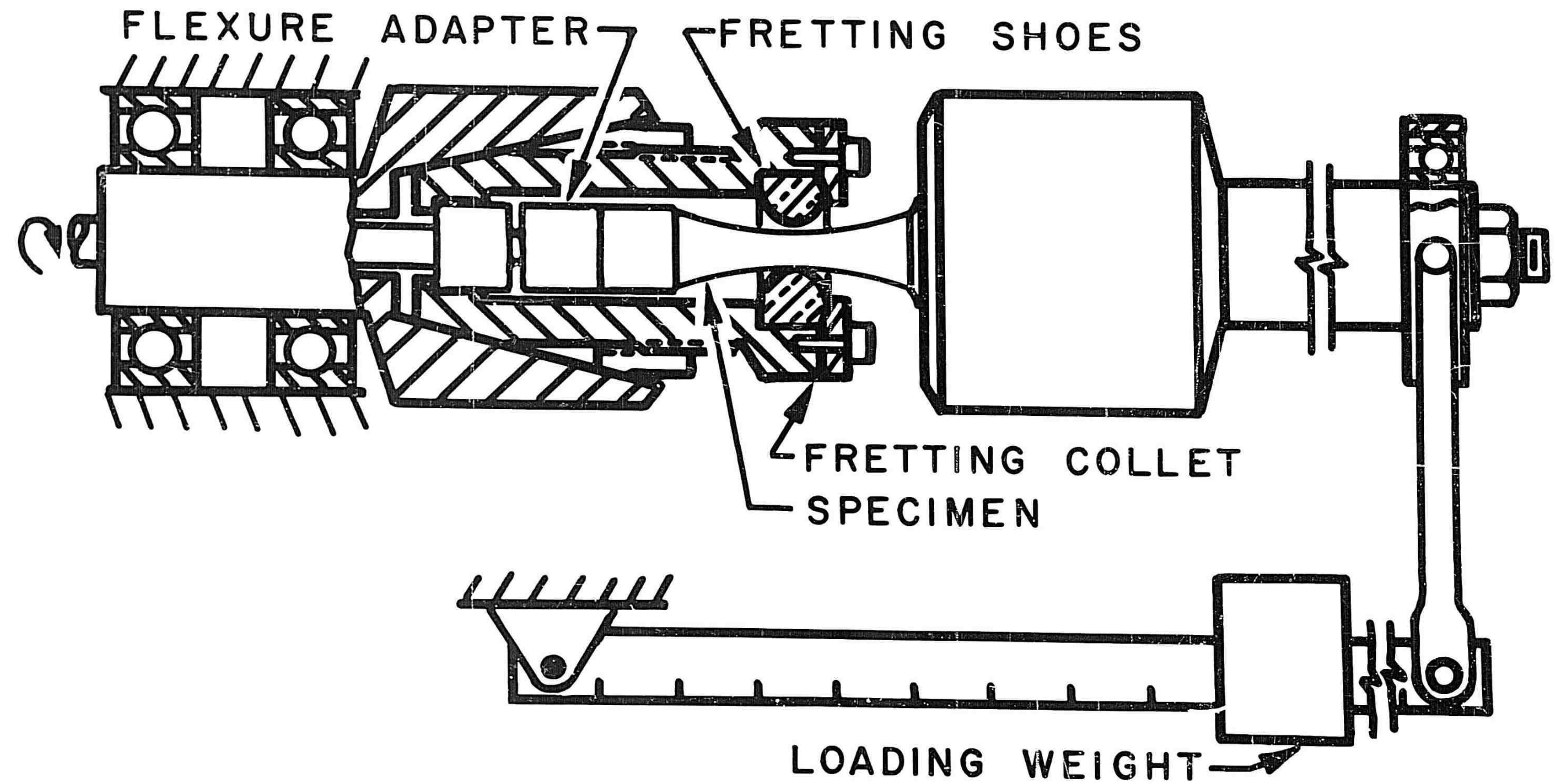
FLEXURE ADAPTER
SPECIMEN
FRETTING SHOES
SHOE RETAINER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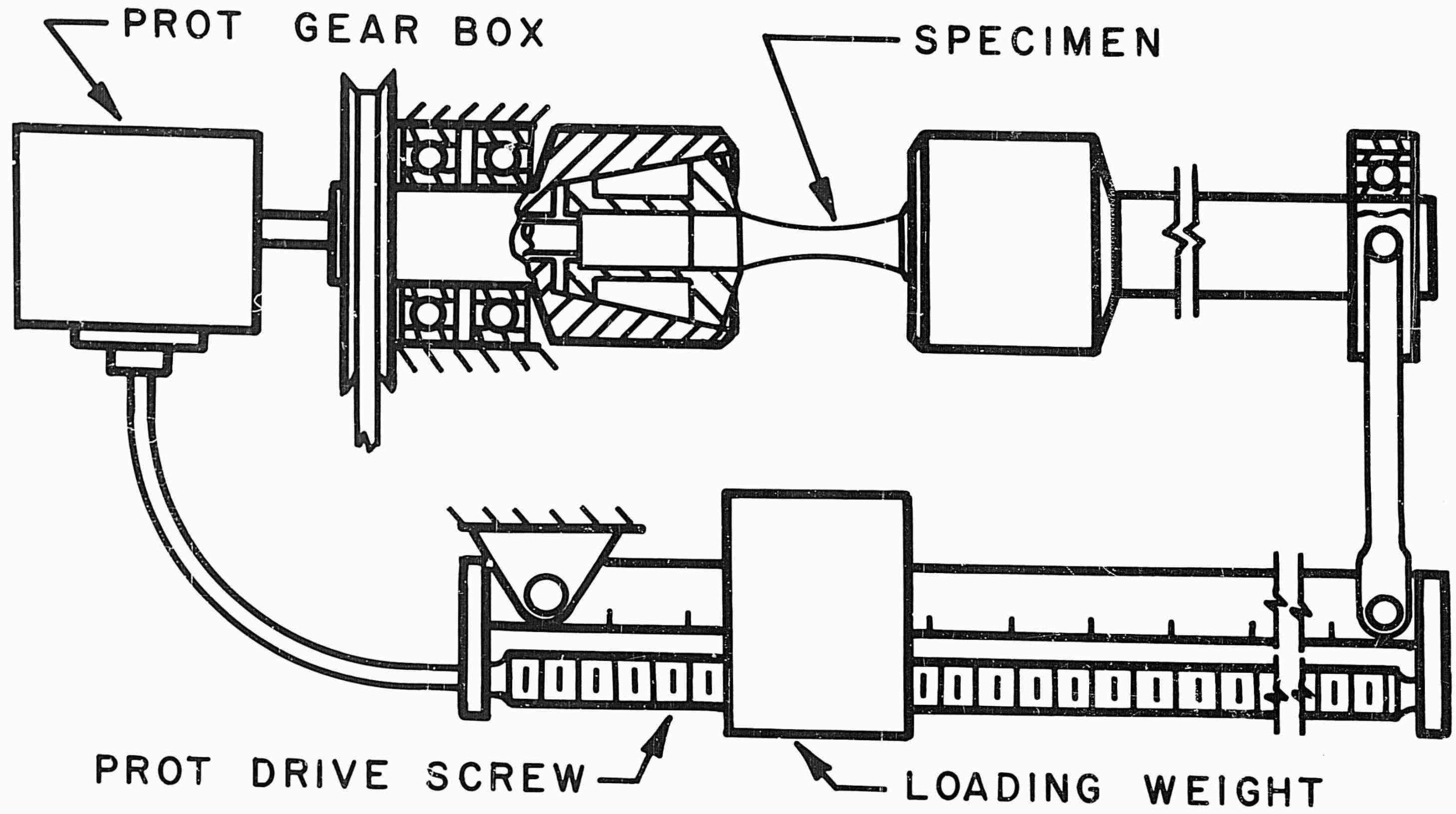
FRETTING SHOES
FRETTING COLLET
SPECIMEN
LOADING WEIGHT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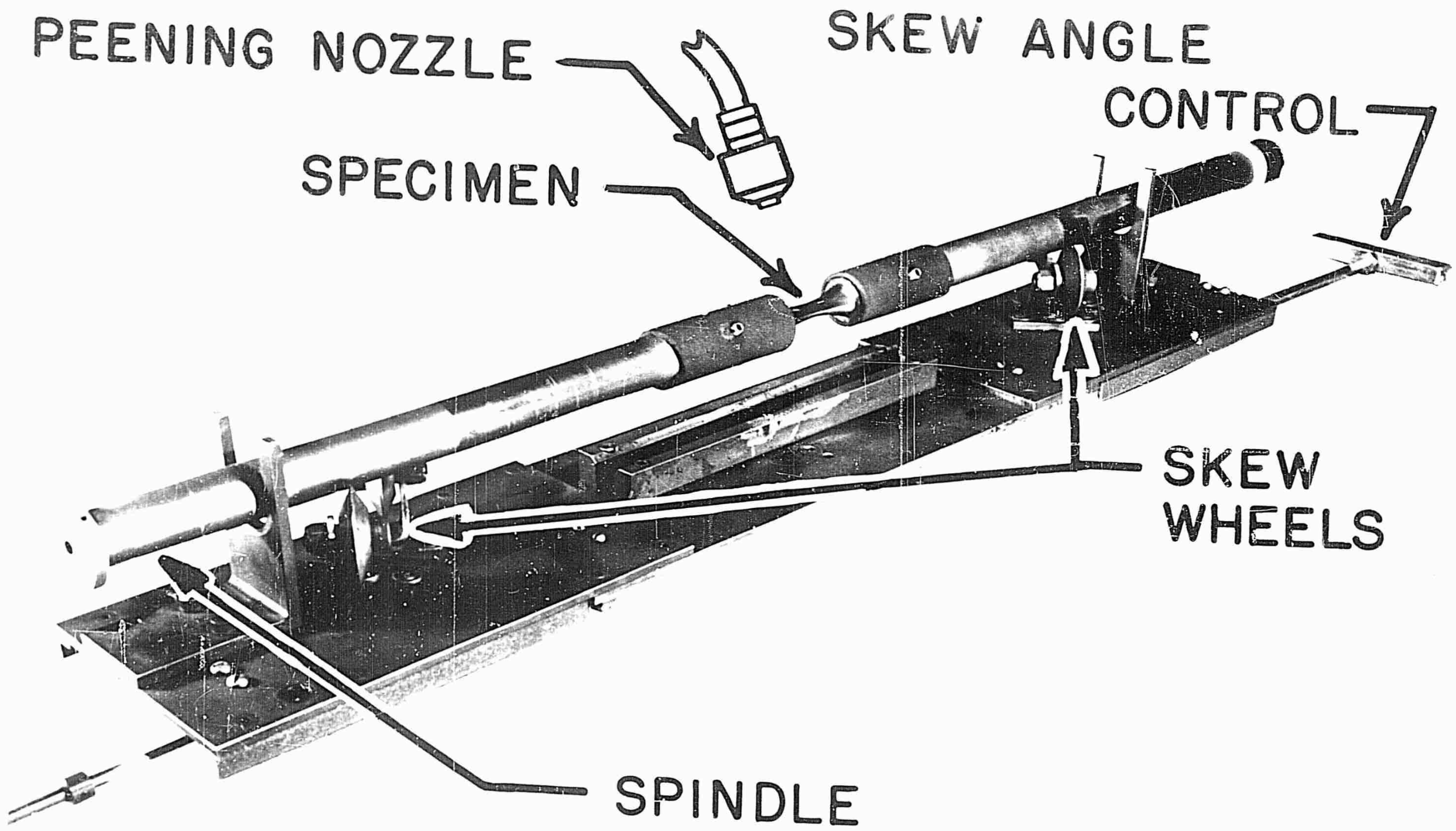
SPECIMEN
PROT DRIVE SCREW
LOADING WEIGHT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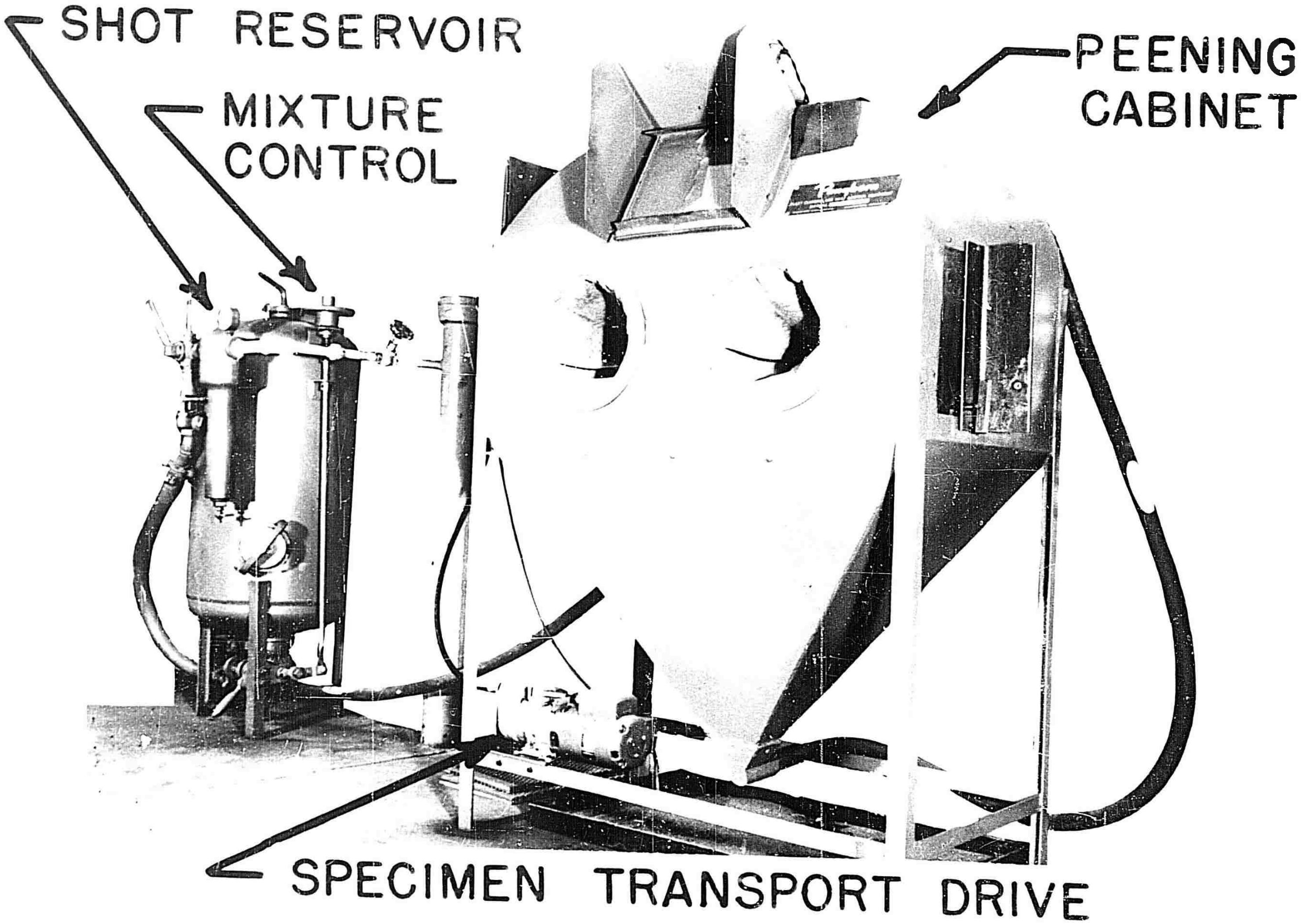
SPECIMEN
SKEW ANGLE CONTROL
SKEW WHEELS
SPINDLE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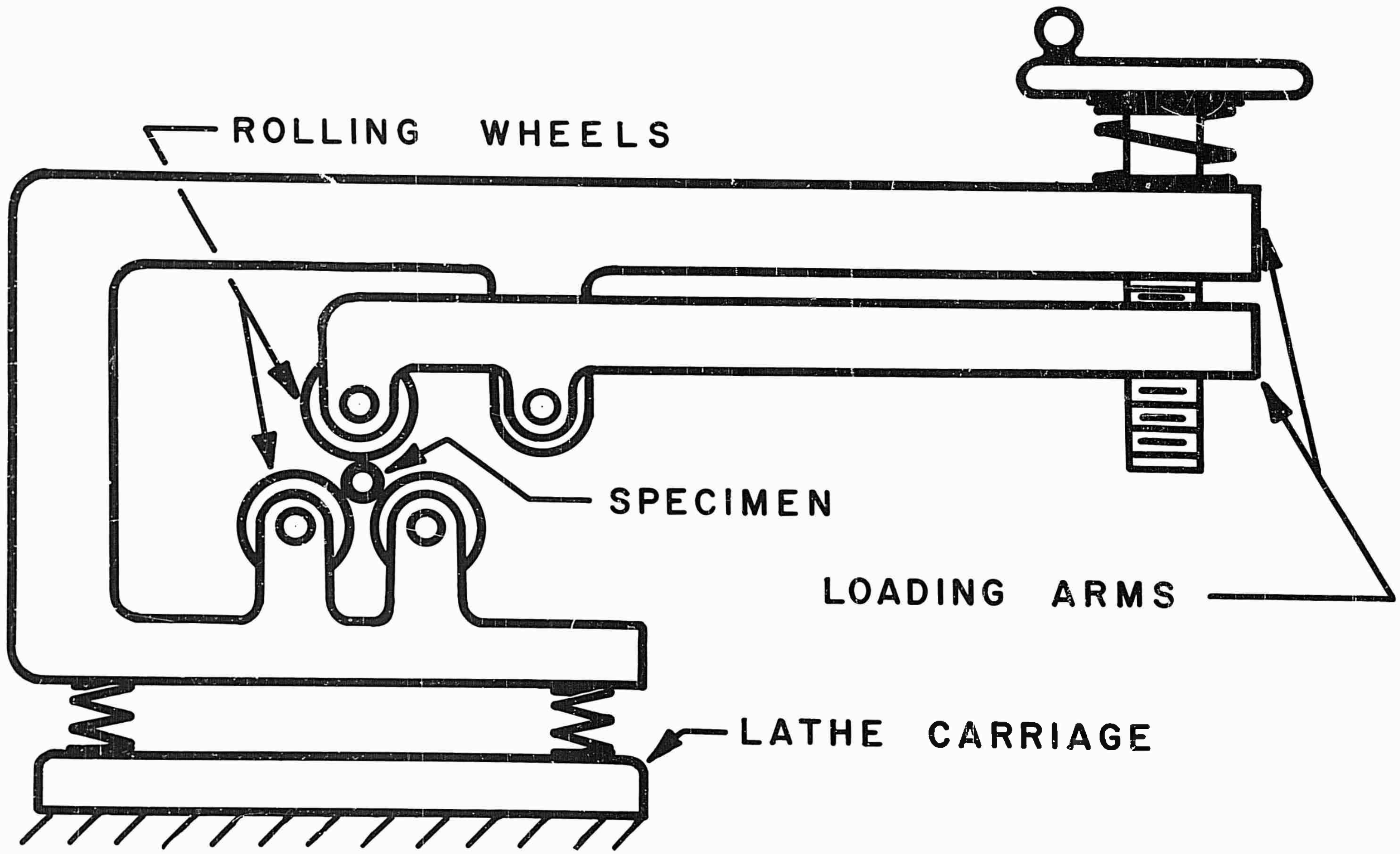
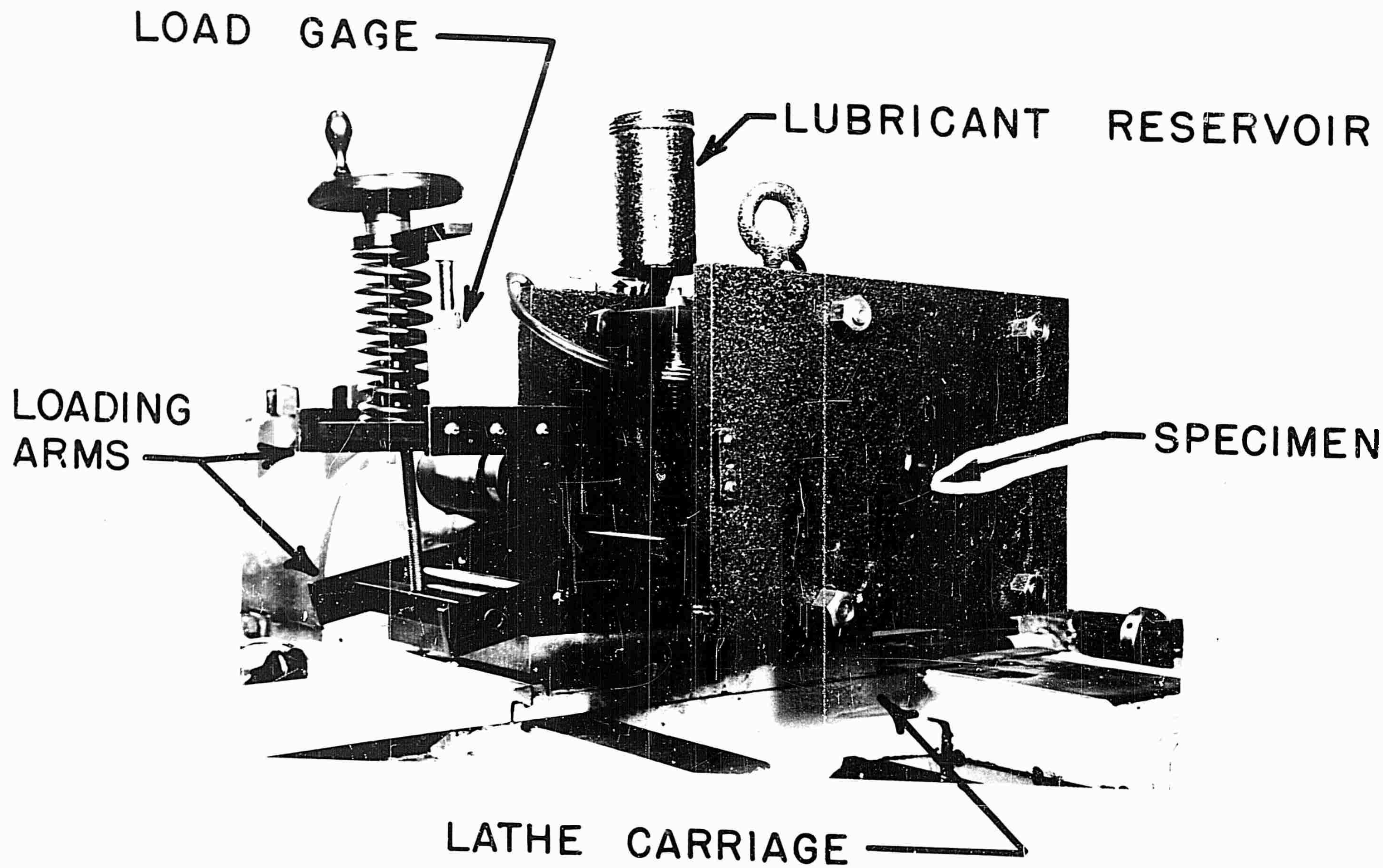
MIXTURE CONTROL
PEENING CABINET
SPECIMEN TRANSPORT DRIVE


ROLLING WHEELS
SPECIMEN
LOADING ARMS
LATHE CARRIAGE


LOAD GAGE
LUBRICANT RESERVOIR
LOADING ARMS
SPECIMEN
LATHE CARRIAGE

SECTION III

EXPERIMENTAL TESTING PROGRAM

3.1 INTRODUCTION

For the purpose of clarity and conciseness in reporting results, the testing program was divided into nine separate tests. Each of these tests is described briefly below. The results and conclusions from each test are presented in Section IV.

3.2 TEST 1—LONG-RUNNING FRETTING TESTS

This test involved an exploratory investigation of the effectiveness of various surface treatments, such as shot-peening or cold-rolling, in fretting-fatigue damage of Ti-140-A titanium alloy. These tests were conducted under conditions of mild, medium, and severe fretting for several millions of cycles of fretting. The results of this test are discussed in 4.2.

3.3 TEST 2—INVESTIGATION OF PROT RELATIONSHIP FOR Ti-140-A TITANIUM

The purpose of this test was to establish the relationship between Prot failure stress and Prot loading rate for Ti-140-A titanium material. The tests involved four different Prot rates and the results were validated by statistical up and down testing to verify the value of endurance limit determined from the Prot data. The results of this test are discussed in 4.3.

3.4 TEST 3—COMPARISON OF ENDURANCE LIMITS OF TWO HEATS OF Ti-140-A TITANIUM MATERIAL

The purpose of this test was to perform a statistically significant comparison between the simple endurance limits of two different heats of Ti-140-A titanium alloy with the same nominal composition. The results of this test are discussed in 4.4.

3.5 TEST 4—COLLECTION OF SUPPLEMENTARY DATA

The purpose of this test was to provide statistically significant endurance limit data for Ti-140-A titanium specimens under four different test conditions: (1) polished Ti-140-A specimens subjected to no fretting, (2) polished Ti-140-A specimens subjected to severe fretting, (3) severely shot-peened Ti-140-A specimens subjected to severe fretting, and (4) severely cold-rolled Ti-120-A specimens subjected to severe fretting. The results of this test are discussed in 4-5.

3.6 TEST 5—EFFECT OF CYCLIC FRETTING FREQUENCY

The purpose of this test was to determine what effect, if any, the cyclic frequency of fretting has on the endurance limit of fretted Ti-140-A specimens. Tests were conducted over a speed range of 100 rpm to 7000 rpm under severe fretting conditions. The results of this test are discussed in 4.6.

3.7 TEST 6--STUDY OF MECHANISM OF FRETTING INHIBITION BY SURFACE TREATMENT

The purpose of this test was to study the basic mechanism by which surface treatments, such as shot-peening and cold-rolling, tend to inhibit fretting-fatigue failure. This study involved a microscopic and macroscopic examination of specimens previously subject to various combinations of surface treatment and fretting. The results of this test are discussed in 4.7.

3.8 TEST 7--DESIGN OF WIRE FRETTING MACHINE

The purpose of this phase of the research was to design, construct, and proof test a machine to subject wire specimens to controlled fretting in either of two mutually perpendicular directions. One direction was to be parallel to the wire axis and the other was to be in the circumferential direction. This test is discussed in 4.8.

3.9 TEST 8—WIRE FRETTING-FATIGUE TESTS

The purpose of this test was to perform fretting tests on wire specimens to compare the effects of fretting in the axial direction with fretting in the circumferential direction. Such information would provide data useful in evaluating the relative contributions of the pit-digging action and the asperity-contact action to the total fretting damage. Fretting damage was to be measured by reduction in endurance limit as determined statistically using up and down test methods. This test is discussed in 4.9.

3.10 TEST 9—EXPLORATORY ANALYSIS OF FRETTING-FATIGUE PHENOMENON

The purpose of this test was to maintain an up-to-date literature file on fretting-fatigue and associated phenomena, and to explore the possibility of developing a fretting-fatigue design equation. The results of this investigation are discussed in 4-10.

SECTION IV

RESULTS AND CONCLUSIONS

4.1 INTRODUCTION

For the purpose of orderly performance and clarity in reporting, the research program was divided into nine separate parts as described in Section III. The detailed results of each test are discussed in the following paragraphs and pertinent conclusions are presented.

4.2 TEST 1--LONG-RUNNING FRETTING TESTS

Exploration of the effectiveness of surface treatment in controlling fretting damage was of primary importance in this investigation. Former studies* had indicated that shot-peening and cold-rolling titanium specimens prior to application of 100,000 cycles of fretting greatly improved the fatigue endurance properties of the fretted materials. Test 1 was designed to provide similar information for much larger numbers of fretting cycles.

Two types of surface treatments were used -- shot-peening and cold-rolling. After the surface treatment, each specimen was subjected to a mild, medium, or severe fretting treatment for several million cycles. The details of the shot-peening treatments, cold-rolling treatments, and fretting treatments are shown in Tables B-1, B-2 and B-3 of Appendix B.

During the fretting process each test specimen was treated in one of two different ways. Either it was disassembled from the shoe, cleaned, measured, and weighed each 500,000 cycles of fretting, or it was permitted to run the entire specified test time without disassembly.

Figures 4-1 through 4-10 and Table B-4 of Appendix B show the trend appears to be uniform. For both weight loss and diameter change, the tendency is to a very low rate of change for the first one to two million cycles followed by an abrupt upswing in the rate after this early period. This abrupt upturn seems to occur when the motions between shoe and specimen become so large that debris is lost and the process degenerates into galling and severe wear action. It is interesting to note that in many cases the fretting shoes actually decrease in internal diameter, which means that metal transfer must occur from specimen to shoe.

To illustrate the relative severity of fretting action, Tables 4-1 and 4-2 present specimen weight loss and diameter change data for various combinations of surface treatment and fretting action after one and one-half million cycles of fretting. Both the estimated arithmetic mean and estimated unbiased standard deviation are presented for each set of conditions used.

* See Ref. 26

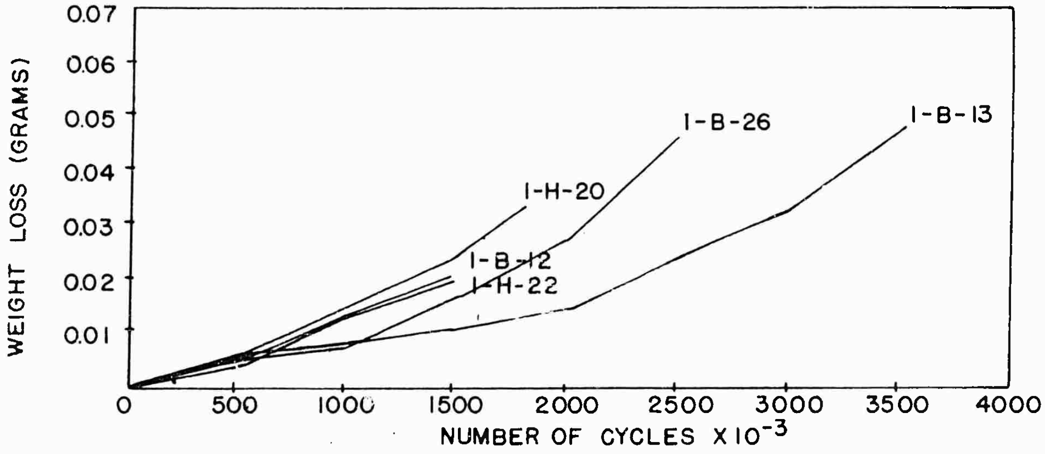
Table 4-1 Summary of Titanium Specimen Weight Loss Data After 1.5 Million Fretting Cycles

Surface Treatment	Degree of Fretting	Mean Weight Loss, gram	Unbiased Standard Deviation
Severely Shot-Peened	Mild	.0055	.00332
Severely Cold-Rolled	Medium	.0075	.00434
Severely Shot-Peened	Medium	.0106	.06420
Severely Cold-Rolled	Severe	.0175	.00494
Severely Shot-Peened	Severe	.0349	.00923

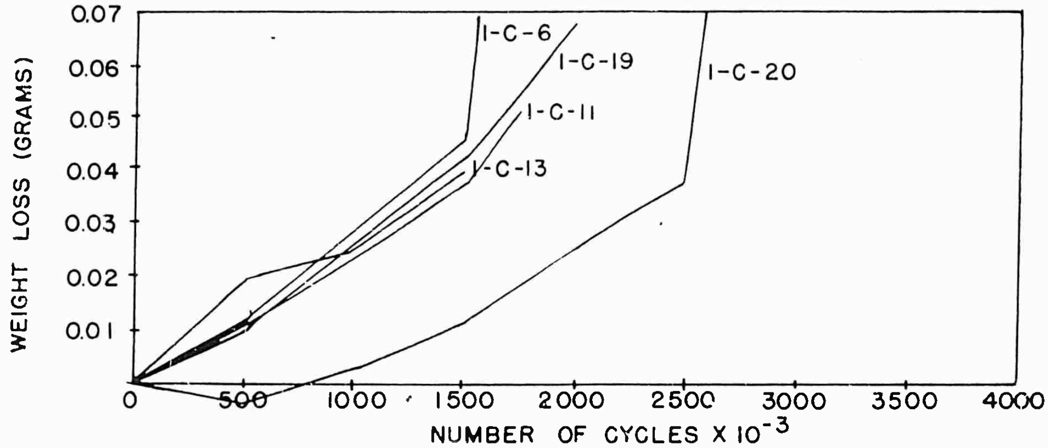
Table 4-2 Summary of Titanium Specimen Diameter Loss Data After 1.5 Million Fretting Cycles

Surface Treatment	Degree of Fretting	Mean Diam. Loss, inch	Unbiased Standard Deviation
Severely Cold-Rolled	Medium	.00021	.000214
Severely Cold-Rolled	Severe	.00024	.000133
Severely Shot-Peened	Mild	.00133	.000922
Severely Shot-Peened	Medium	.00202	.001248
Severely Shot-Peened	Severe	.00559	.000522

Figures 4-11 through 4-22 and Table B-5 of Appendix B show weight loss and diameter change data for specimens cleared of debris each 500,000 cycles compared with specimens not cleared of debris throughout the test. A summary of these data is given in Tables 4-3 and 4-4 showing the mean and standard deviation for cleared and uncleared specimens after one and one-half million cycles of fretting.

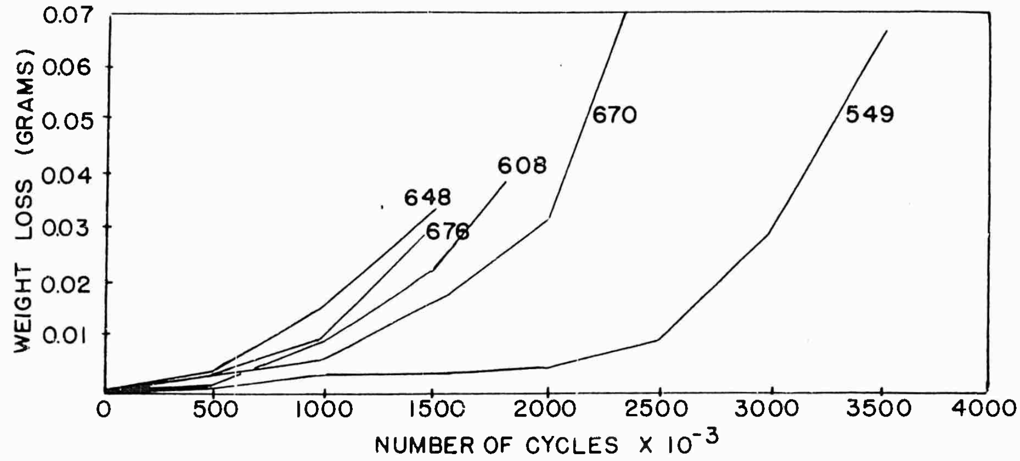


SEVERELY COLD ROLLED SPECIMENS

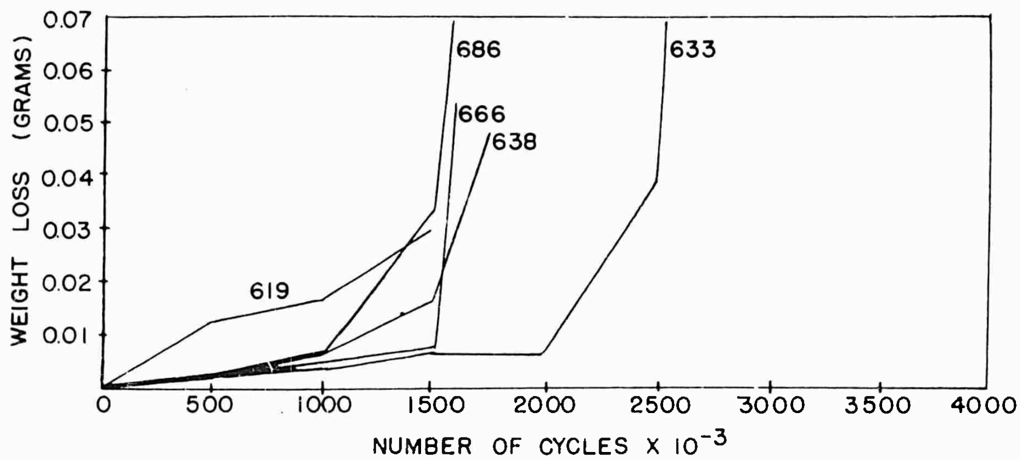


SEVERELY SHOT PEENED SPECIMENS

FIGURE 4-1 WEIGHT LOSS VERSUS NUMBER OF FRETTING CYCLES FOR TI 140-A TITANIUM SPECIMENS WITH VARIOUS SURFACE TREATMENTS SUBJECTED TO SEVERE FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

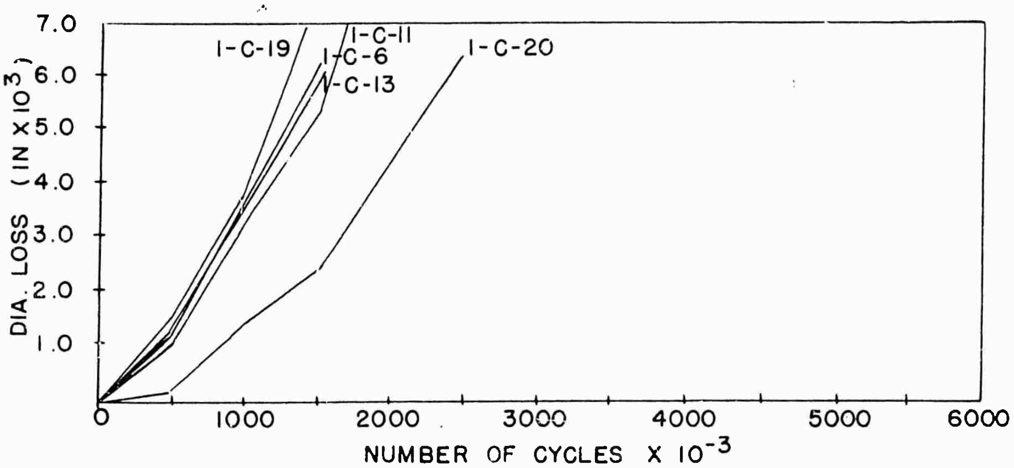


SHOES FOR SEVERELY COLD ROLLED SPECIMENS

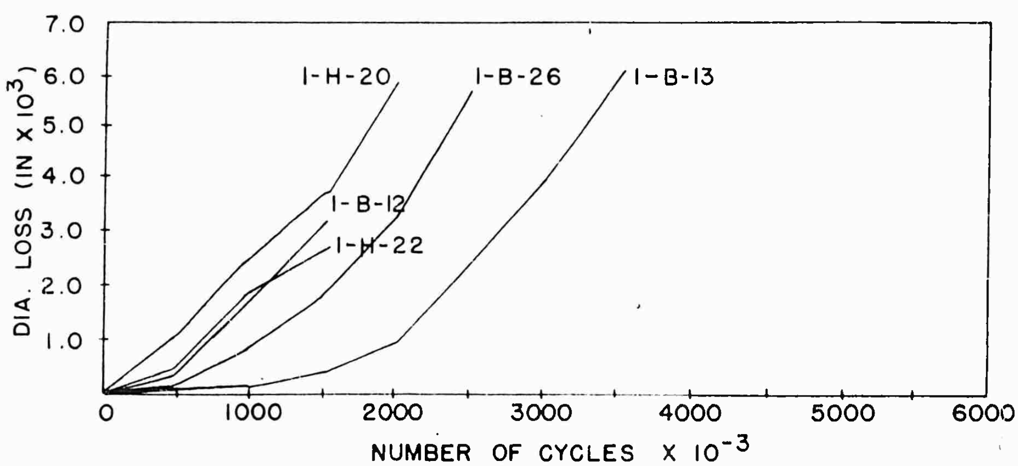


SHOES FOR SEVERELY SHOT PEENED SPECIMENS

FIGURE 4-2 WEIGHT LOSS VERSUS NUMBER OF FRETTING CYCLES FOR SAE 4340 STEEL SHOES USED WITH TITANIUM SPECIMENS SUBJECTED TO SEVERE FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

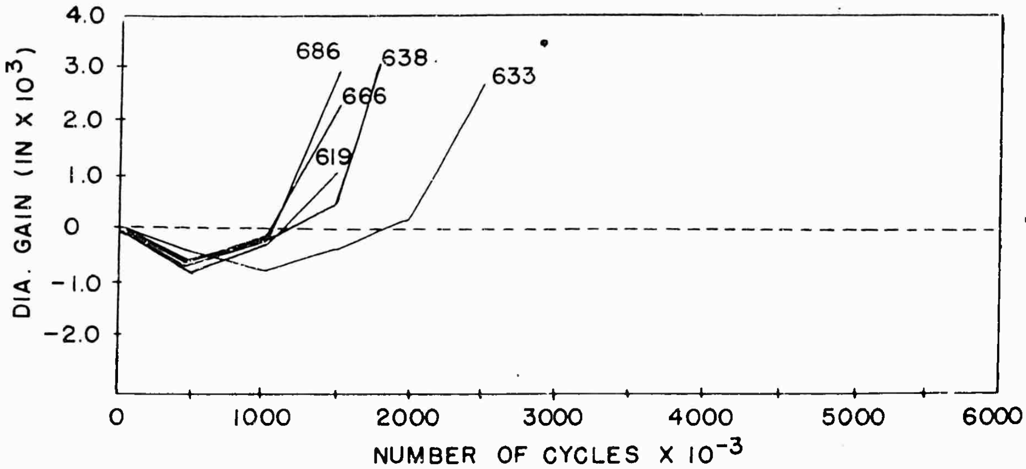


SEVERELY SHOT PEENED SPECIMENS

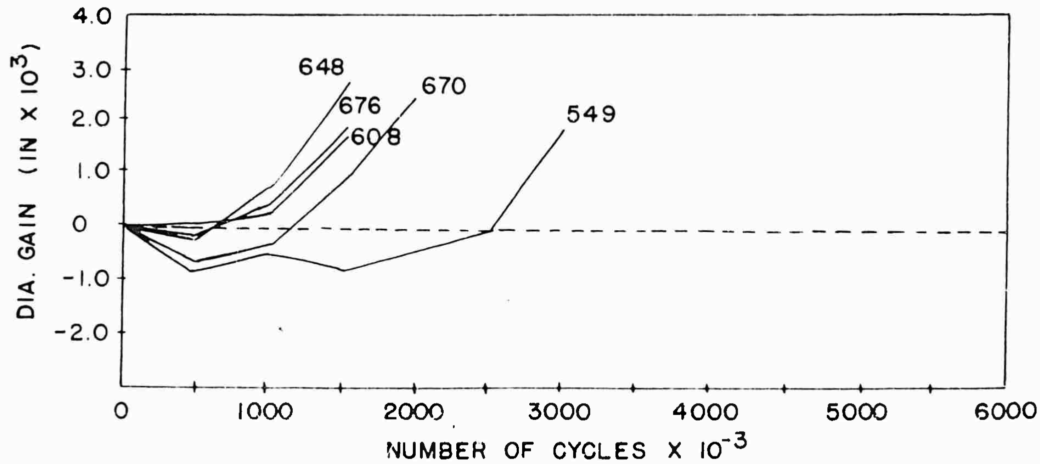


SEVERELY COLD ROLLED SPECIMENS

FIGURE 4-3 DECREASE IN MEAN DIAMETER VERSUS NUMBER OF FRETTING CYCLES FOR TI 140-A TITANIUM SPECIMENS WITH VARIOUS SURFACE TREATMENTS SUBJECTED TO SEVERE FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

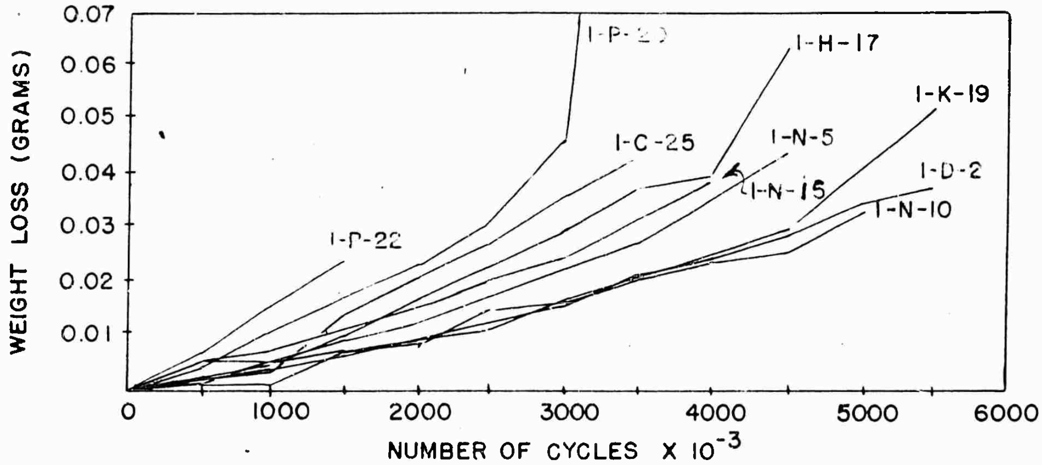


SHOES FOR SEVERELY SHOT PEENED SPECIMENS

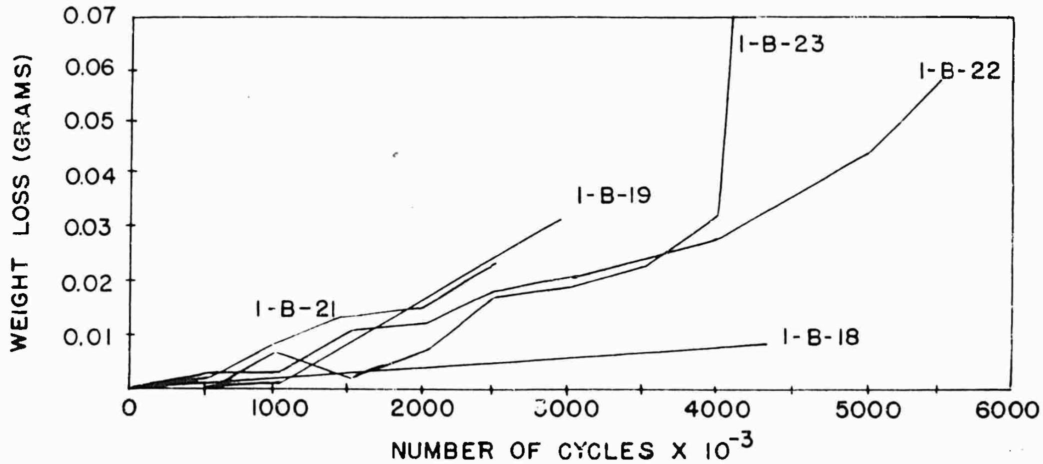


SHOES FOR SEVERELY COLD ROLLED SPECIMENS

FIGURE 4-4 INCREASE IN MEAN DIAMETER VERSUS NUMBER OF FRETTING CYCLES FOR SAE 4340 STEEL SHOES USED WITH TITANIUM SPECIMENS SUBJECTED TO SEVERE FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

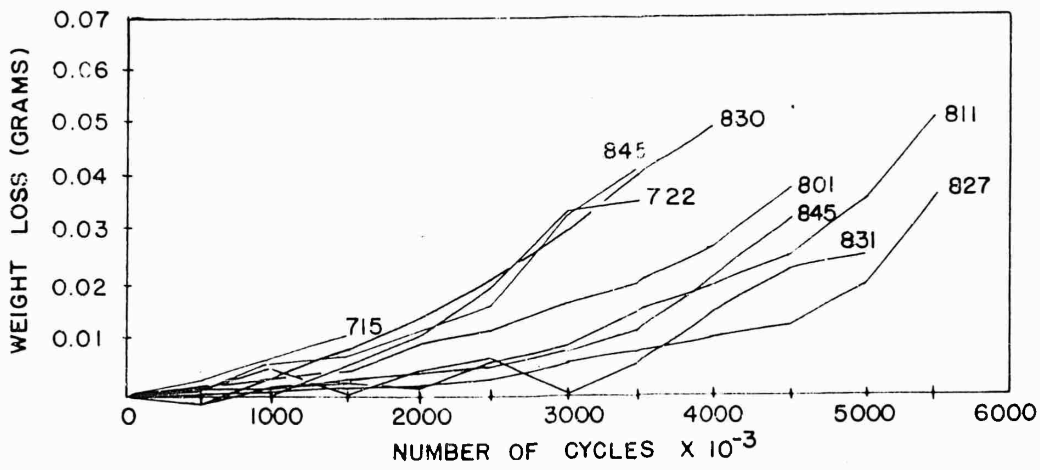


SEVERELY SHOT PEENED SPECIMENS

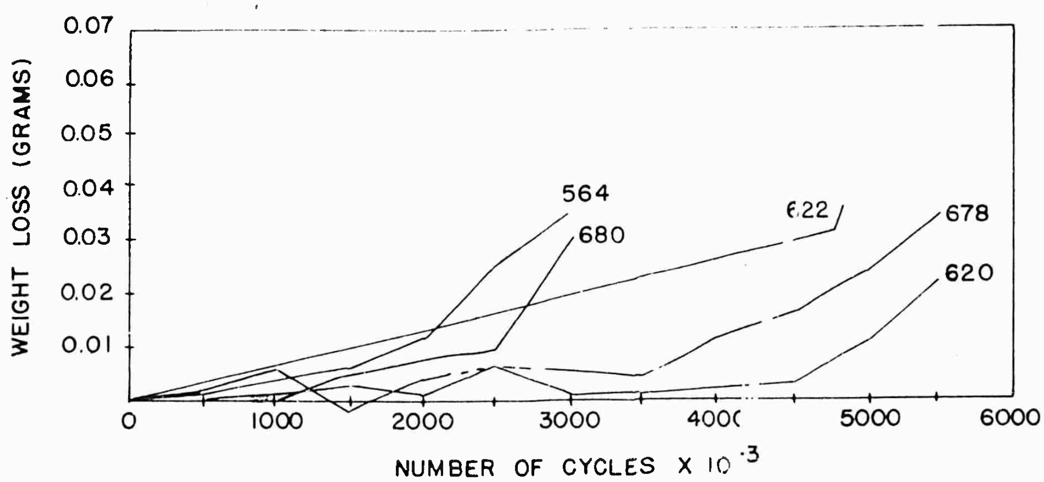


SEVERELY COLD ROLLED SPECIMENS

FIGURE 4-5 WEIGHT LOSS VERSUS NUMBER OF FRETTING CYCLES FOR TI-140-A TITANIUM SPECIMENS WITH VARIOUS SURFACE TREATMENTS SUBJECTED TO MEDIUM FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

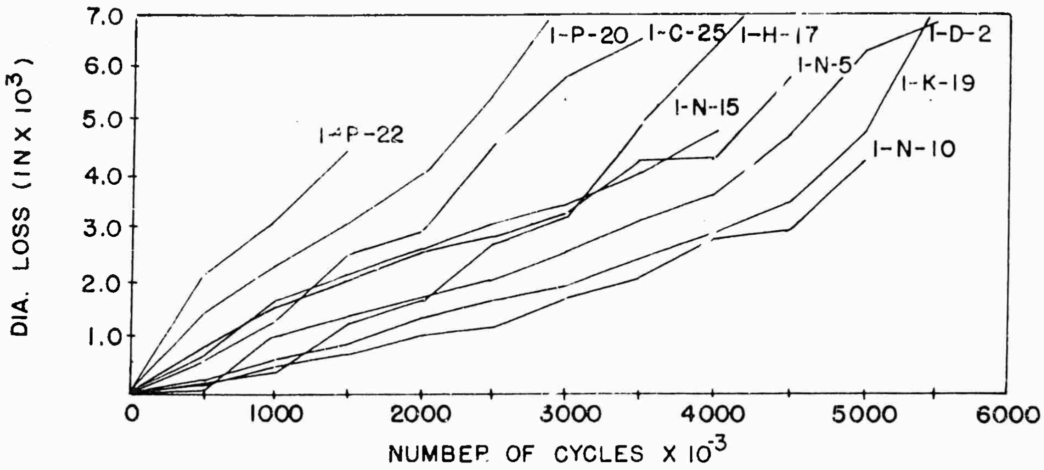


SHOES FOR SEVERELY SHOT PEENED SPECIMENS

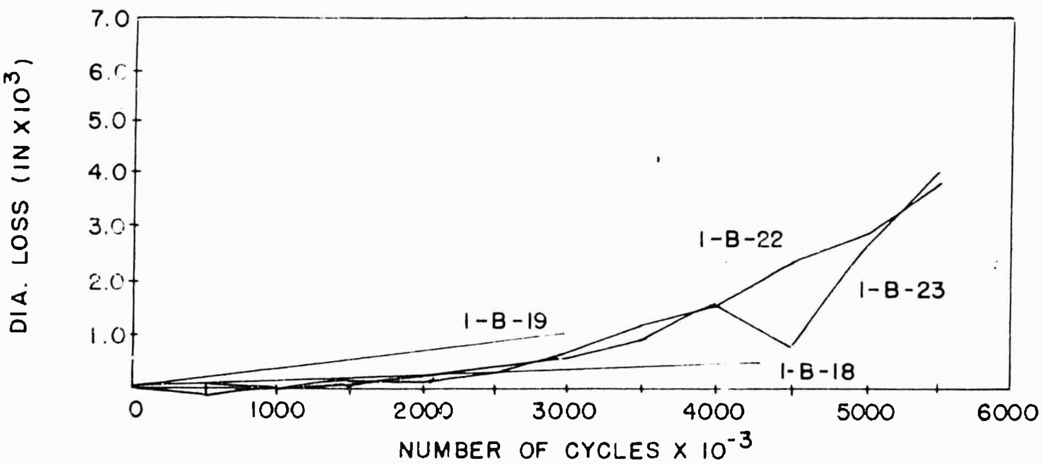


SHOES FOR SEVERELY COLD ROLLED SPECIMENS

FIGURE 4-6 WEIGHT LOSS VERSUS NUMBER OF FRETTING CYCLES FOR SAE 4340 STEEL SHOES USED WITH TITANIUM SPECIMENS SUBJECTED TO MEDIUM FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

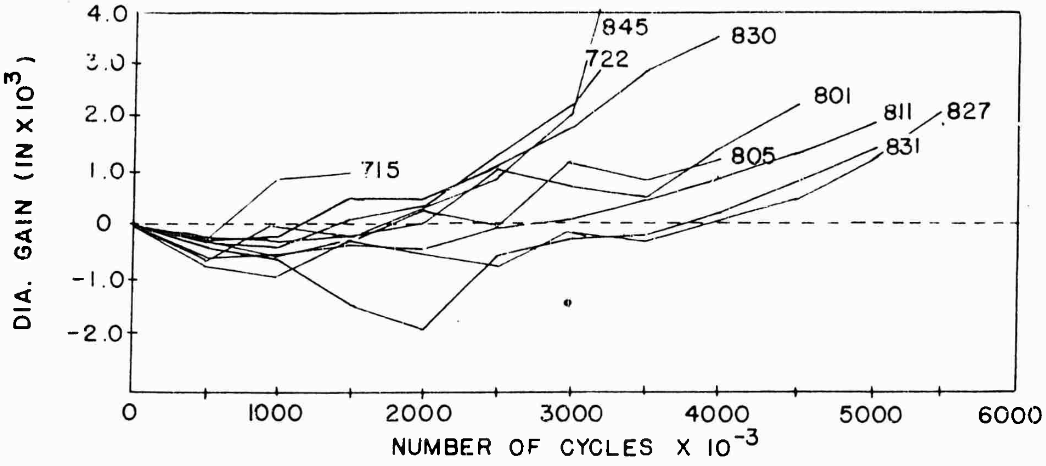


SEVERELY SHOT PEENED SPECIMENS

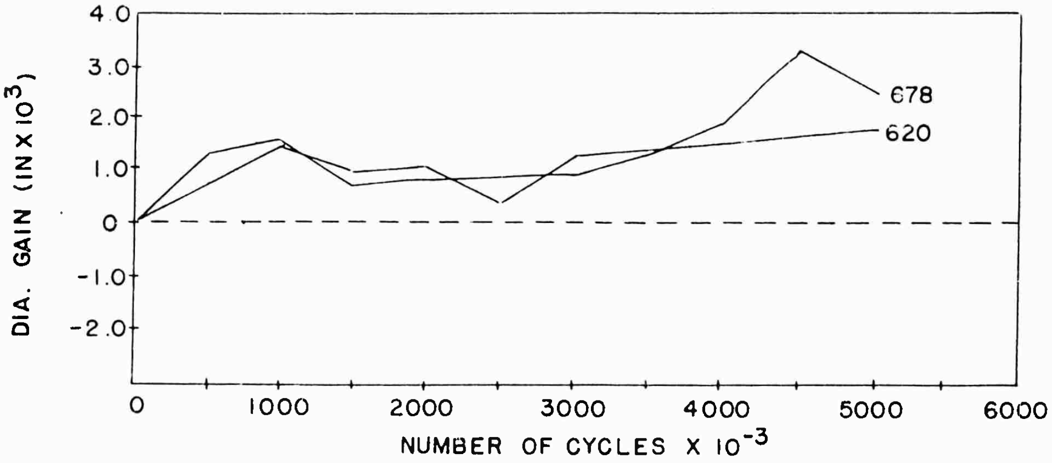


SEVERELY COLD ROLLED SPECIMENS

FIGURE 4-7 DECREASE IN MEAN DIAMETER VERSUS NUMBER OF FRETTING CYCLES FOR TI 140-A TITANIUM SPECIMENS WITH VARIOUS SURFACE TREATMENTS SUBJECTED TO MEDIUM FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

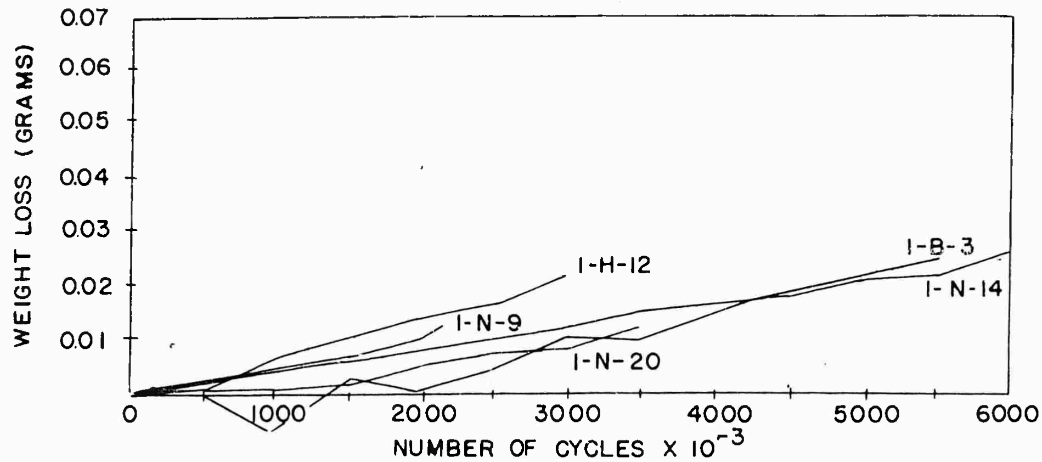


SHOES FOR SEVERELY SHOT PEENED SPECIMENS

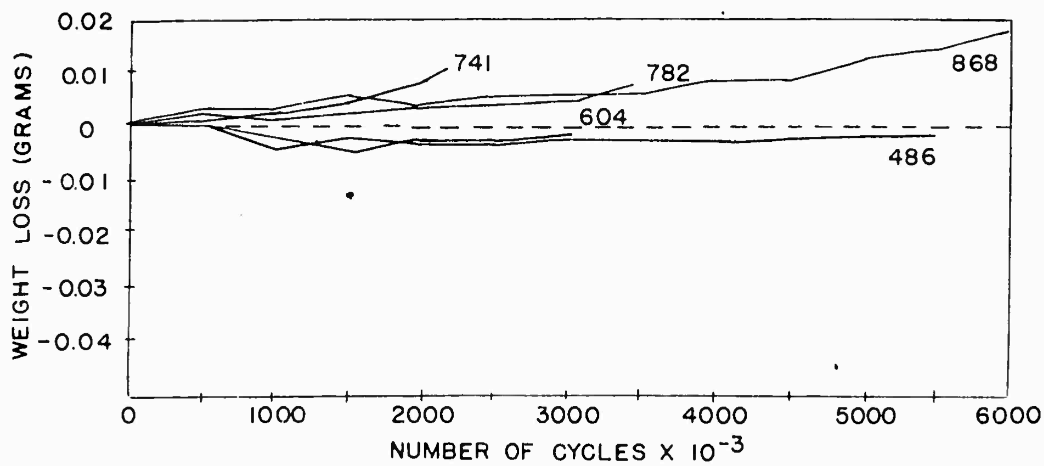


SHOES FOR SEVERELY COLD ROLLED SPECIMENS

FIGURE 4-8 INCREASE IN MEAN DIAMETER VERSUS NUMBER OF FRETTING CYCLES FOR SAE 4340 STEEL SHOES USED WITH TITANIUM SPECIMENS SUBJECTED TO MEDIUM FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING.

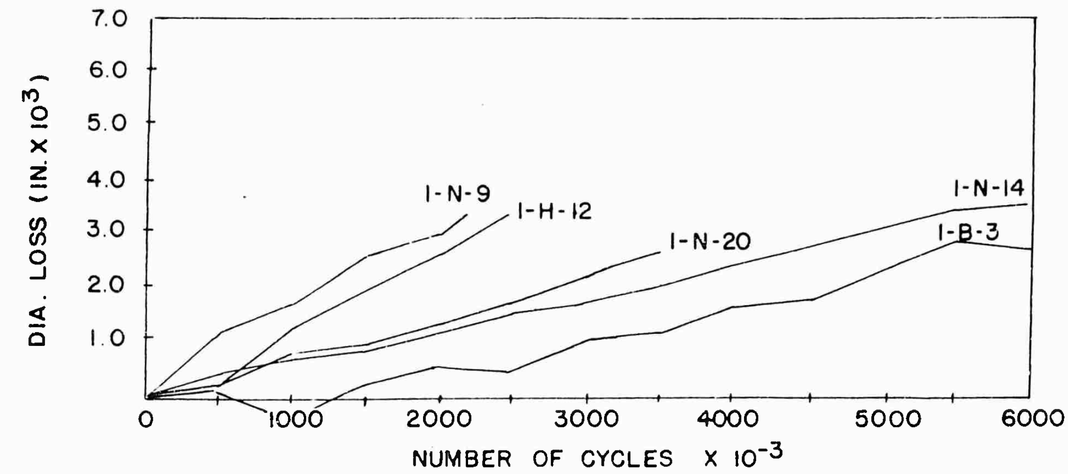


SEVERELY SHOT PEENED SPECIMENS

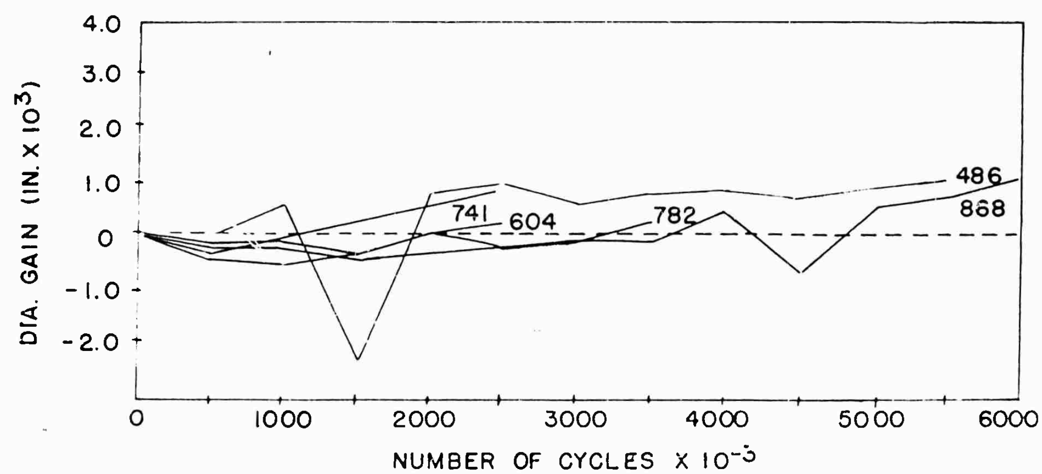


SHOES FOR SEVERELY SHOT PEENED SPECIMENS

FIGURE 4-9 WEIGHT LOSS VERSUS NUMBER OF FRETTING CYCLES FOR SEVERELY SHOT PEENED TI 140-A TITANIUM SPECIMENS SUBJECTED TO MILD FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING AND SAE 4340 STEEL SHOES USED IN THE FRETTING TREATMENT.



SEVERELY SHOT PEENED SPECIMENS



SHOES FOR SEVERELY SHOT PEENED SPECIMENS

FIGURE 4-10 DIAMETER CHANGE VERSUS NUMBER OF FRETTING CYCLES FOR SEVERELY SHOT PEENED TI 140-A TITANIUM SPECIMENS SUBJECTED TO MILD FRETTING CONDITIONS FOR LARGE NUMBERS OF CYCLES OF FRETTING AND SAE 4340 STEEL SHOES USED IN THE FRETTING TREATMENT.

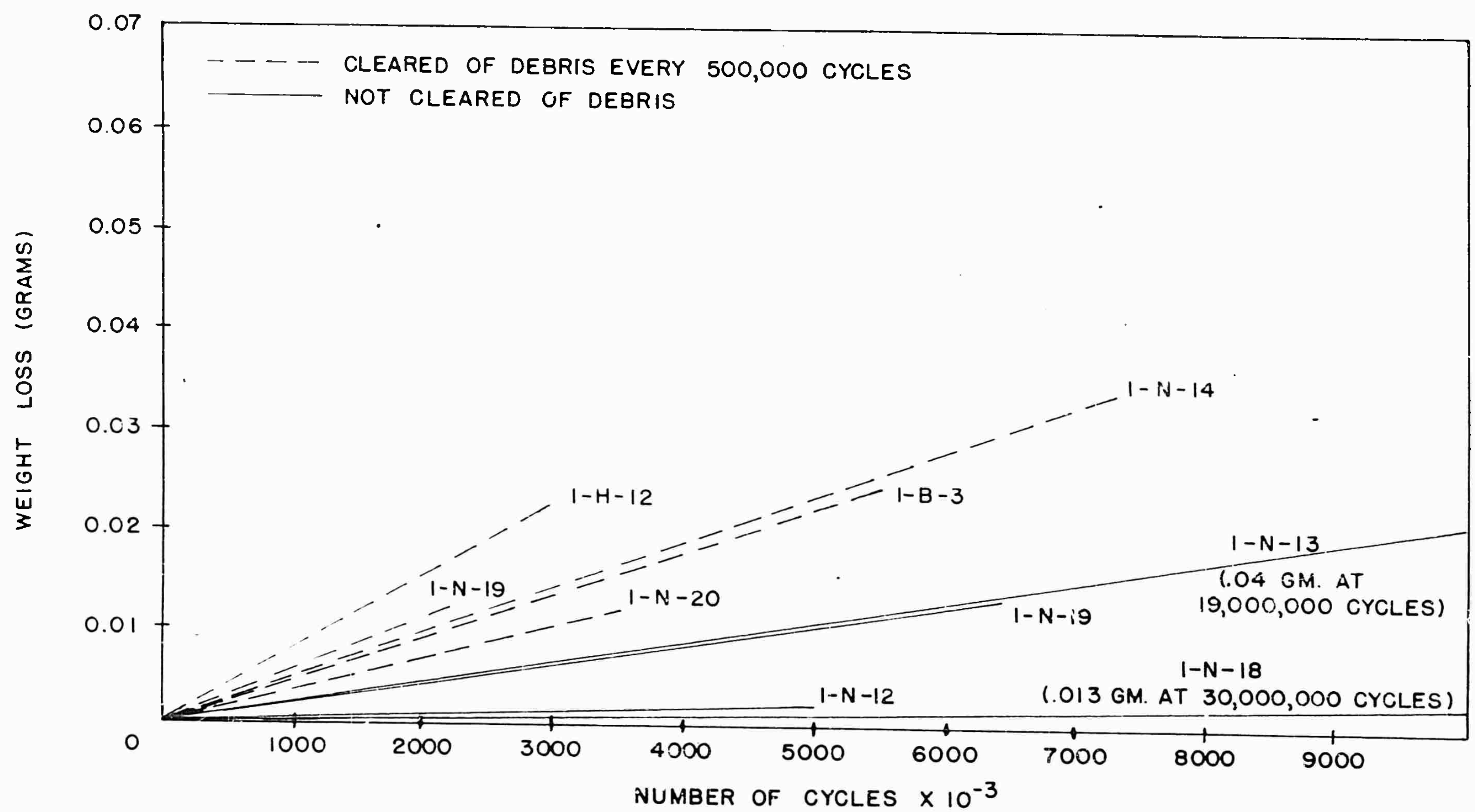


FIGURE 4-11 COMPARISON OF WEIGHT LOSSES FOR SPECIMENS PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SPECIMENS NOT CLEARED OF DEBRIS. ALL SPECIMENS WERE SEVERELY SHOT-PEENED, MILDLY FRETTED TI-140-A TITANIUM.

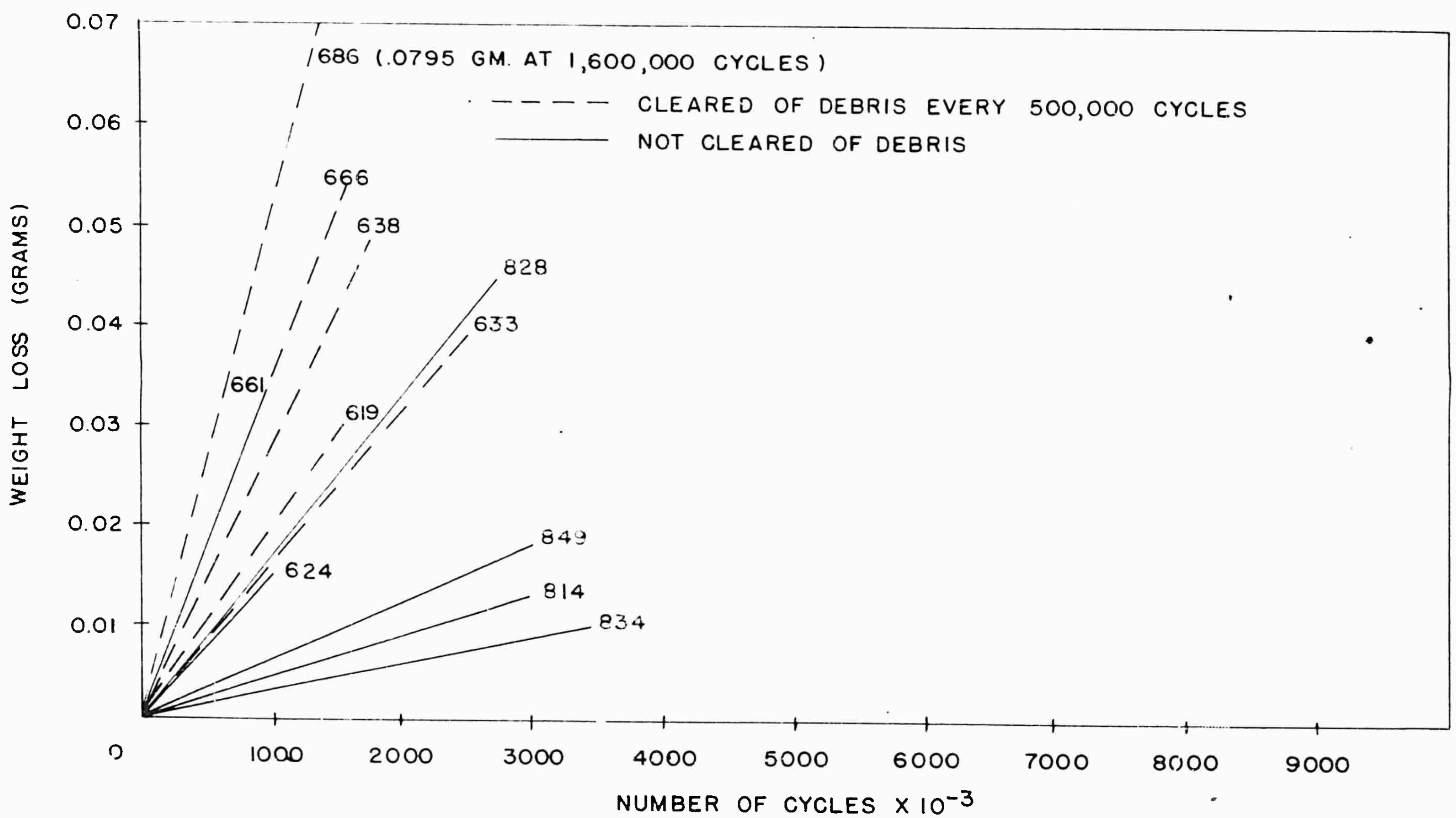


FIGURE 4-12 COMPARISON OF WEIGHT LOSSES FOR SHOES PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SHOES NOT CLEARED OF DEBRIS. ALL SHOES WERE SAE 4340 STEEL AND USED WITH SEVERELY SHOT-PEENED, SEVERELY FRETTED TI-140-A TITANIUM SPECIMENS.

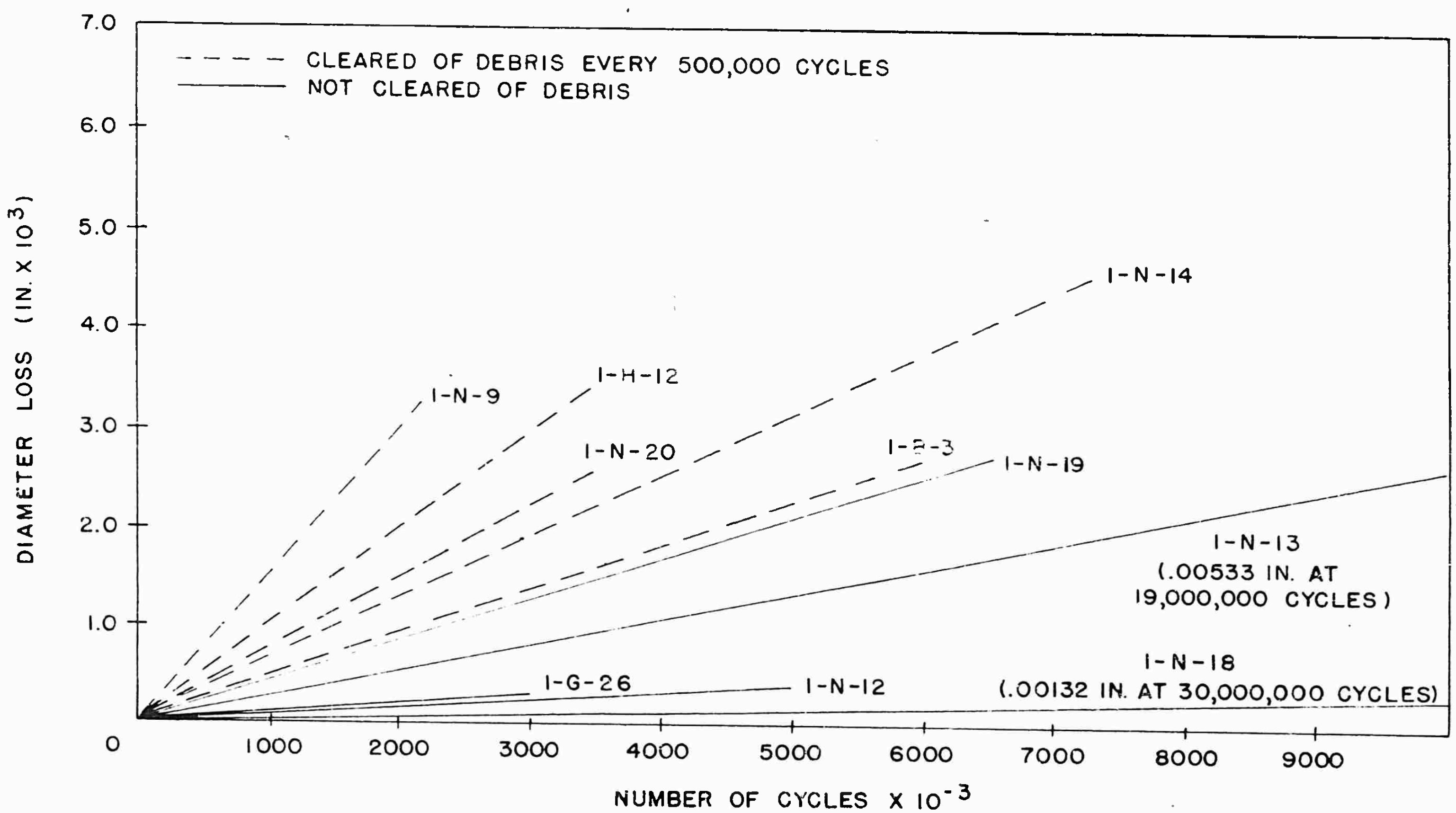


FIGURE 4-13 COMPARISON OF DIAMETER LOSSES FOR SPECIMENS PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SPECIMENS NOT CLEARED OF DEBRIS. ALL SPECIMENS WERE SEVERELY SHOT-PEENED, MILDLY FRETTED TI-140-A TITANIUM.

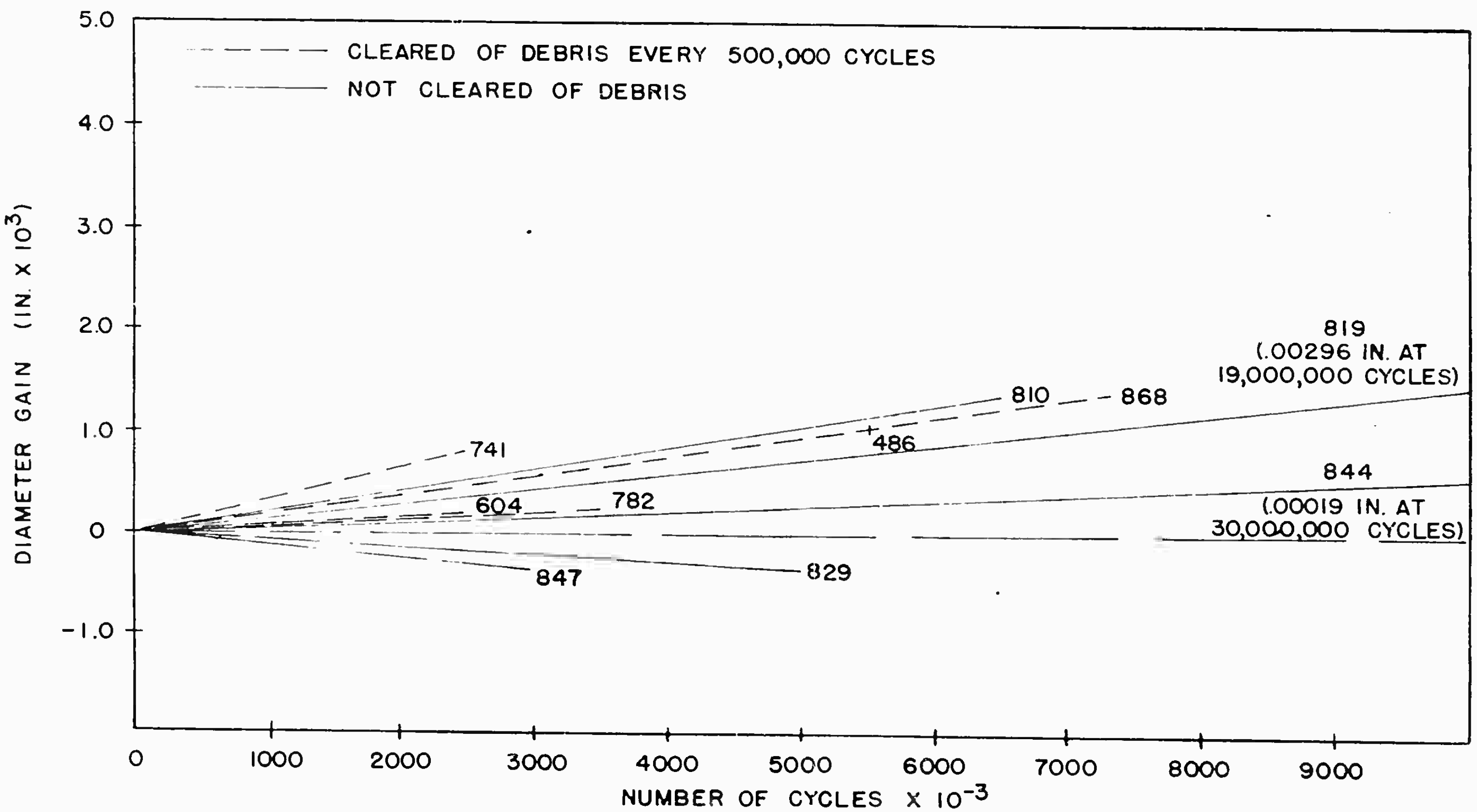


FIGURE 4-14 COMPARISON OF DIAMETER GAINS FOR SHOES PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SHOES NOT CLEARED OF DEBRIS. ALL SHOES WERE SAE 4340 STEEL USED WITH SEVERELY SHOT-PEENED MILDLY FRETTED TI-140-A TITANIUM SPECIMENS.

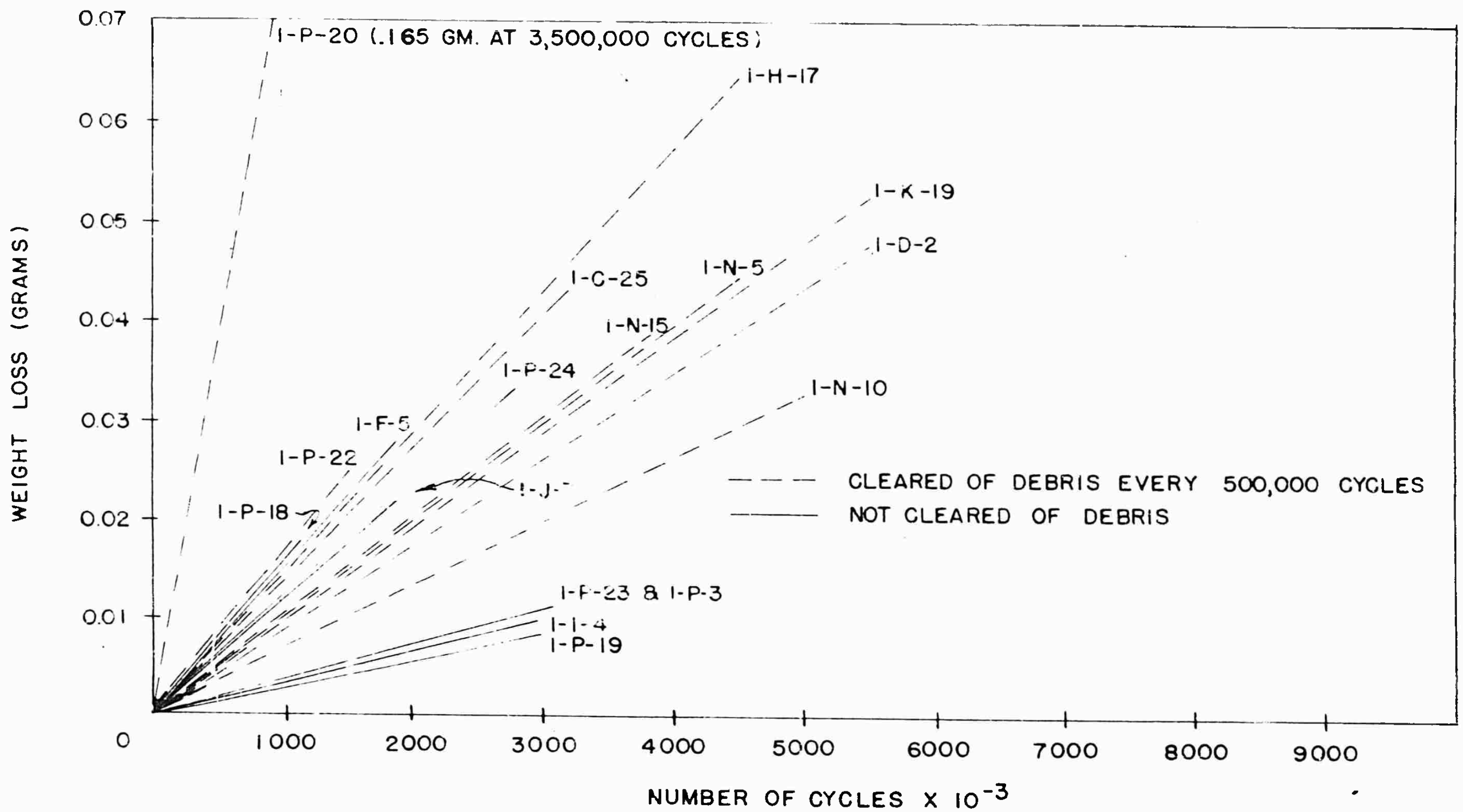


FIGURE 4-15 COMPARISON OF WEIGHT LOSSES FOR SPECIMENS PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SPECIMENS NOT CLEARED OF DEBRIS. ALL SPECIMENS WERE SEVERELY SHOT-PEENED, MEDIALLY FRETTED TI-140-A TITANIUM.

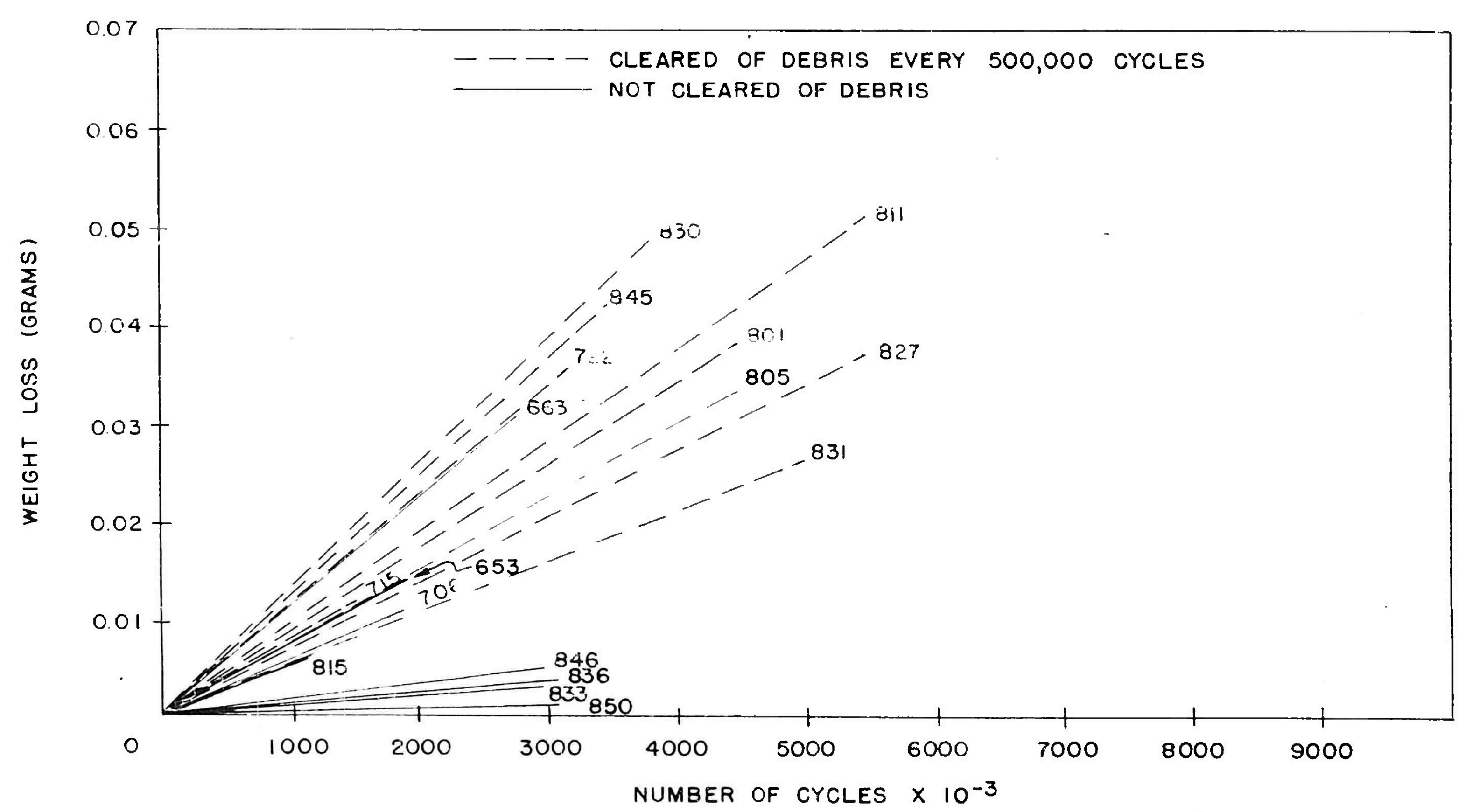


FIGURE 4-16 COMPARISON OF WEIGHT LOSSES FOR SHOES PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SHOES NOT CLEARED OF DEBRIS. ALL SHOES WERE SAE 4340 STEEL AND USED WITH SEVERELY SHOT-PEENED, MEDIALLY FRETTED TI-140-A TITANIUM SPECIMENS.

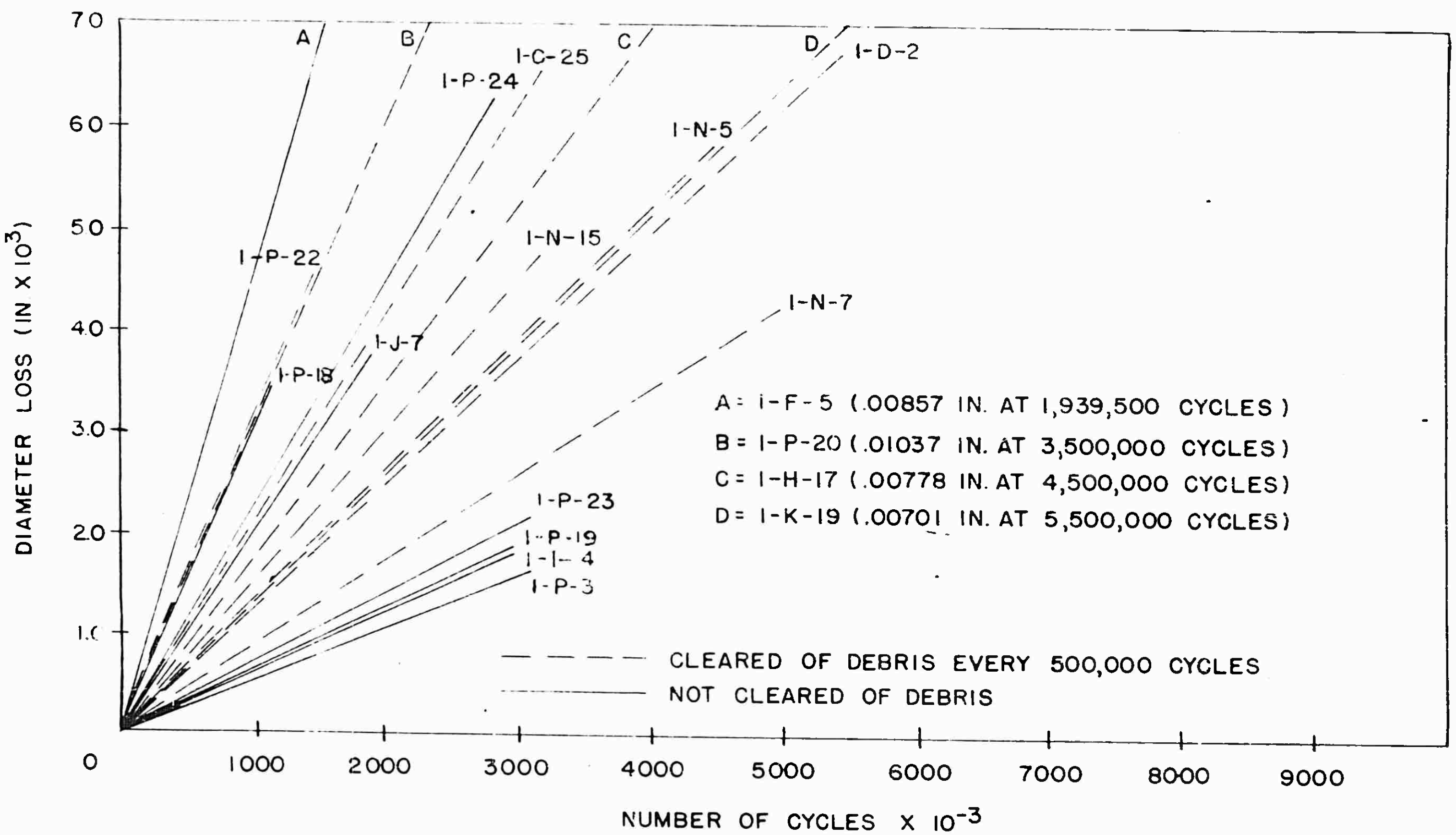


FIGURE 4-17 COMPARISON OF DIAMETER LOSSES FOR SPECIMENS PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SPECIMENS NOT CLEARED OF DEBRIS. ALL SPECIMENS WERE SEVERELY SHOT-PEENED, MEDIALLY FRETTED TI-140-A TITANIUM.

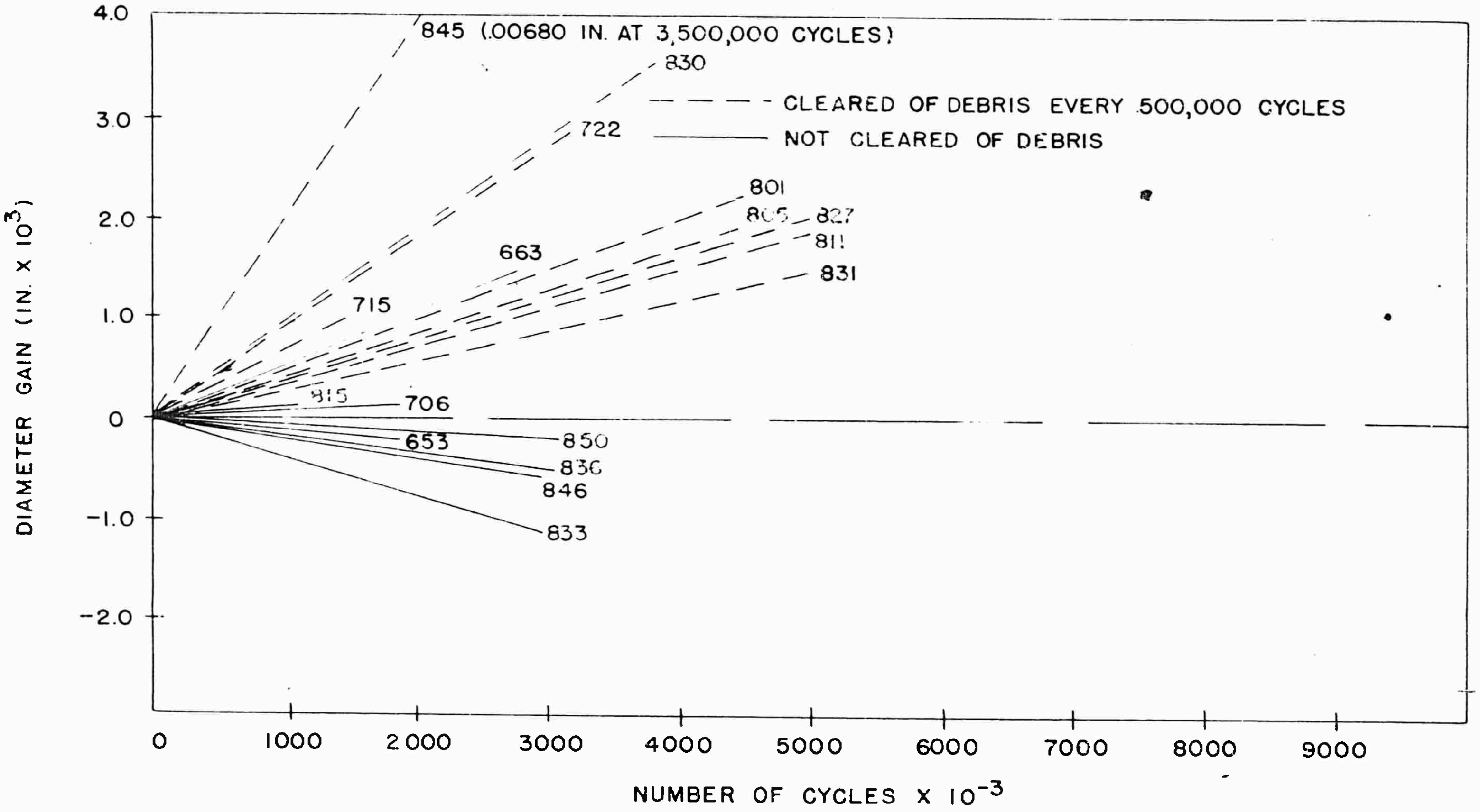


FIGURE 4-18 COMPARISON OF DIAMETER GAINS FOR SHOES PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SHOES NOT CLEARED OF DEBRIS. ALL SHOES WERE SAE 4340 STEEL AND USED WITH SEVERELY SHOT-PEENED, MEDIALLY FRETTED TI-140-A TITANIUM SPECIMENS.

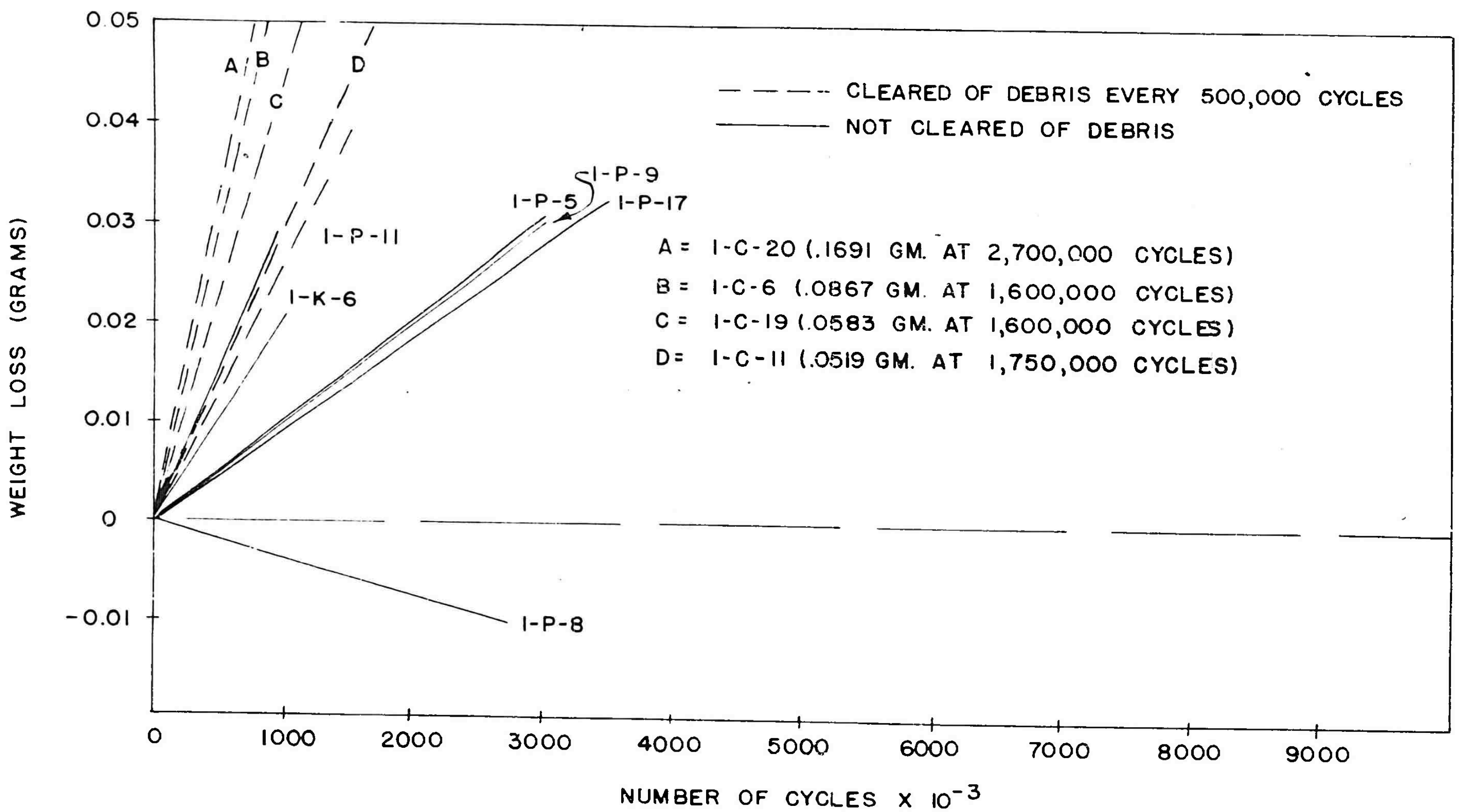


FIGURE 4-19 COMPARISON OF WEIGHT LOSSES FOR SPECIMENS PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SPECIMENS NOT CLEARED OF DEBRIS. ALL SPECIMENS WERE SEVERELY SHOT-PEENED, SEVERELY FRETTED TI-140-A TITANIUM.

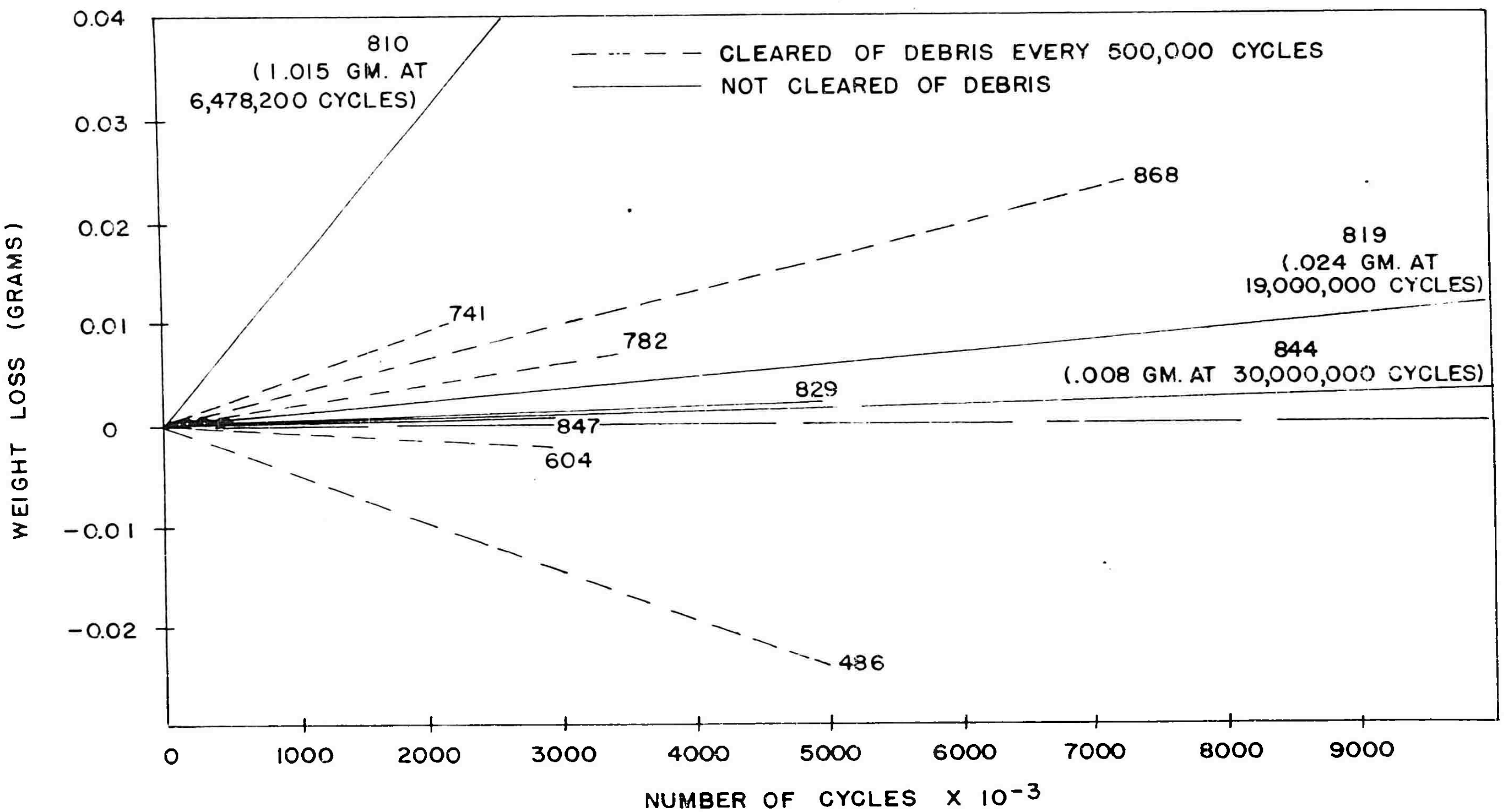


FIGURE 4-20 COMPARISON OF WEIGHT LOSSES FOR SHOES PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SHOES NOT CLEARED OF DEBRIS. ALL SHOES WERE SAE 4340 STEEL AND USED WITH SEVERELY SHOT-PEENED MILDLY FRETTED TI-140-A TITANIUM SPECIMENS.

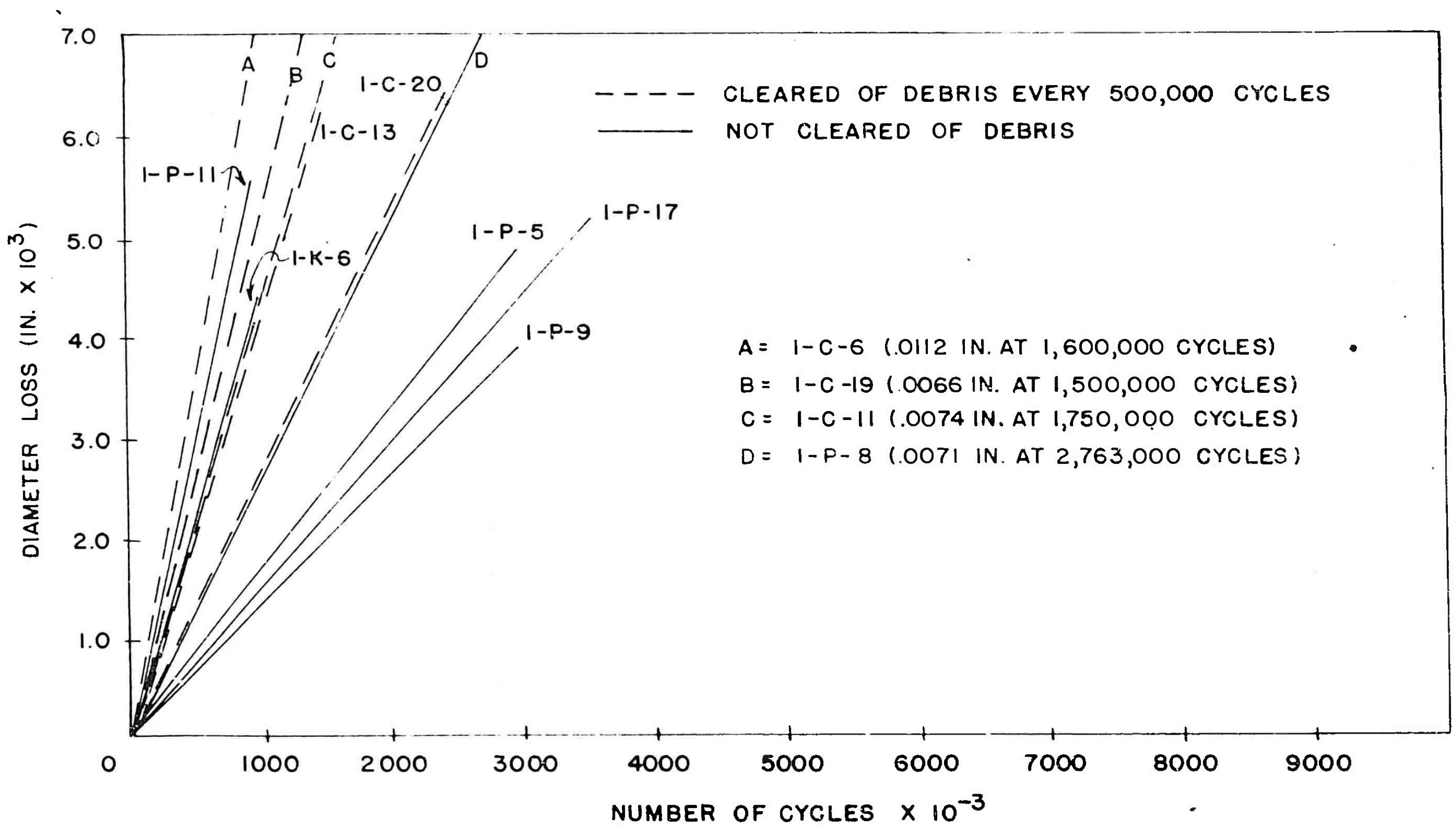


FIGURE 4-21 COMPARISON OF DIAMETER LOSSES FOR SPECIMENS PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SPECIMENS NOT CLEARED OF DEBRIS. ALL SPECIMENS WERE SEVERELY SHOT-PEENED, SEVERELY FRETTED TI-140-A TITANIUM.

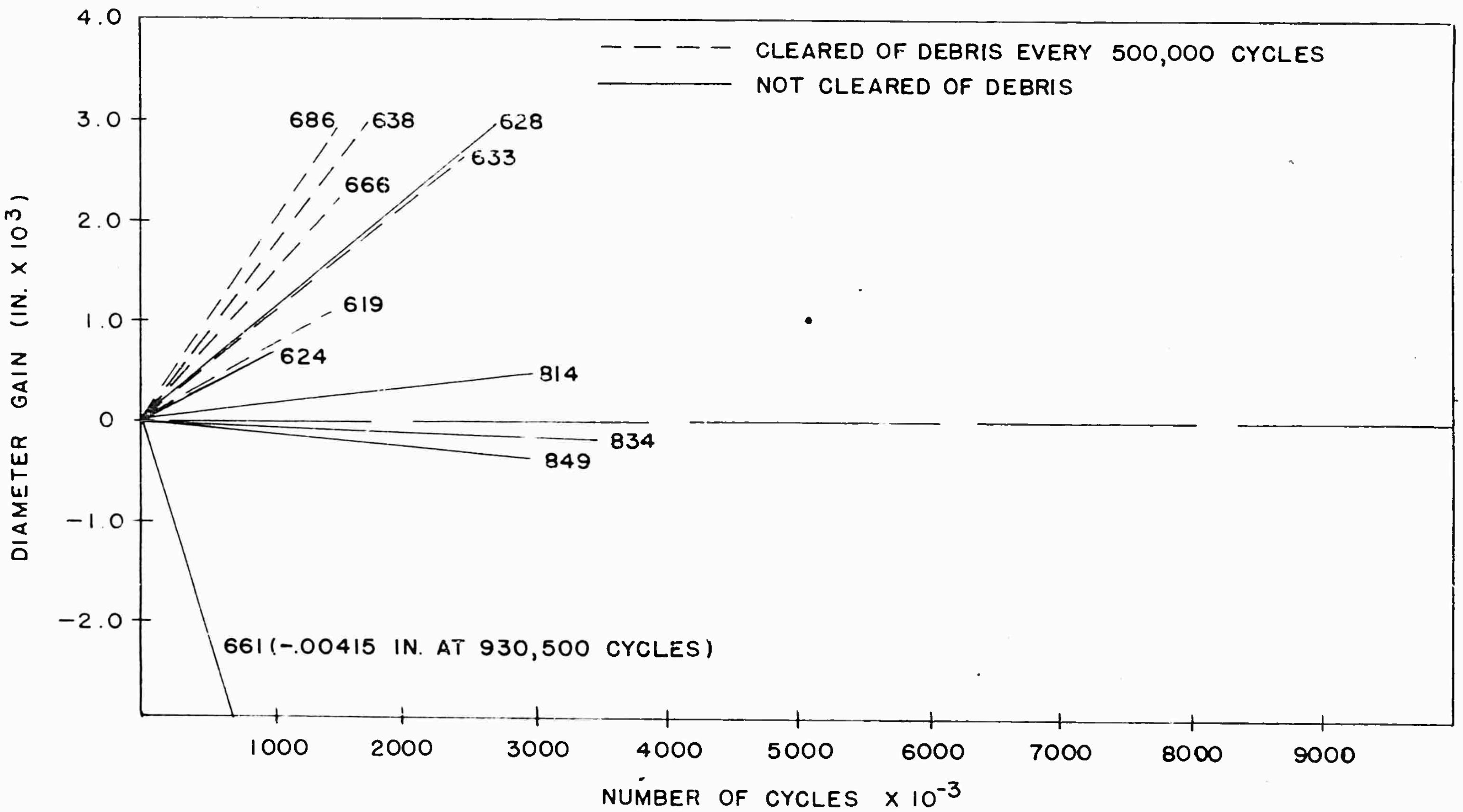


FIGURE 4-22 COMPARISON OF DIAMETER GAINS FOR SHOES PERIODICALLY CLEARED OF DEBRIS DURING THE FRETTING PROCESS WITH SHOES NOT CLEARED OF DEBRIS. ALL SHOES WERE SAE 4340 STEEL AND USED WITH SEVERELY SHOT-PEENED, SEVERELY FRETTED TI-140-A TITANIUM.

Table 4-3. Weight Loss of Severely Shot-Peened Titanium Specimens after 1.5 Million Cycles of Fretting. Comparison of Specimens Cleared of Debris Each 500,000 Cycles with Specimens not Cleared during Entire Test

Degree of Fretting	Mean Weight Loss, gm. Cleared	Mean Weight Loss, gm. Not Cleared	Unbiased Standard Deviation Cleared	Unbiased Standard Deviation Not Cleared
Mild	.0055	.0022	.00332	.00092
Medium	.0106	.00732	.0642	.00561
Severe	.0349	.022	.00923	.01506

Table 4-4. Diameter Loss of Severely Shot-Peened Titanium Specimens after 1.5 Million Cycles of Fretting. Comparison of Specimens Cleared of Debris Each 500,000 Cycles with Specimens not Cleared during Entire Test

Degree of Fretting	Mean Diameter Loss Cleared	Mean Diameter Loss Not Cleared	Unbiased Standard Deviation Cleared	Unbiased Standard Deviation Not Cleared
Mild	.00133	.0000278	.000922	.000339
Medium	.00202	.00180	.001248	.001575
Severe	.00559	.0048	.000522	.00289

From these data, it is interesting to observe that both diameter changes and weight losses are more severe when the specimens are cleaned periodically than when the debris is not cleared during the entire test. This would seem to indicate that the accumulated debris provides a cushion which slows the fretting action.

Figure 4-23 shows the relative endurance limits of specimens subjected to various combinations of surface preparation and fretting for several millions of cycles. Several important observations may be made from these data.

It may be noted that specimens subjected to severe shot-peening tend to exhibit a decreasing endurance limit with increased severity of fretting.

It may be noted that specimens cleared of debris each 500,000 cycles do not show a marked difference in endurance limit from specimens not cleared of debris during an entire test. The amount of scatter for specimens cleared of debris seems to be somewhat greater than for specimens not so cleared.

The endurance limit of severely cold-rolled specimens is little affected by fretting, and the scatter is relatively low. This important result is also supplemented by Figures 4-1, 4-3, 4-5, and 4-7 all of which tend to indicate that weight loss and diameter loss of severely cold-rolled specimens seem to be noticeably less than for shot-peened specimens.

The important general conclusion to be drawn from this exploratory test series is that, while severe shot-peening is an effective fretting-fatigue inhibitor, severe cold-rolling is a better method of inhibiting both fretting wear and fretting-fatigue from the standpoint of maintaining a high mean endurance limit with a small amount of scatter for fretting situations involving several million cycles. This conclusion, of course, is based on a relatively small sample size and must be interpreted with care. Nevertheless, Figure 4-23 presents a strong case for such a conclusion.

4.3 TEST 2--INVESTIGATION OF PROT RELATIONSHIP FOR Ti-140-A TITANIUM

To determine the endurance limit of a specimen by the Prot method, it is necessary to know the Prot rate (rate of stress increase per cycle), the Prot failure stress, and the functional relationship between Prot rate and Prot failure stress for any particular material. It is then possible to calculate the fatigue endurance limit for each specimen. For steel the functional relationship between Prot rate and Prot failure stress has been established, but for titanium it has not.

Test No. 2 had as its objective the determination of a relationship between Prot rate and Prot failure stress for Ti-140-A titanium alloy. Four different Prot rates were used to establish this relationship. These were 0.0025 psi per cycle, 0.01 psi per cycle, 0.04 psi per cycle, and 0.09 psi per cycle. The results of these data are tabulated in Table B-6 of Appendix B.

Figure 4-24 displays the data from the Prot evaluation test. Sixty specimens were tested to provide an accurate relationship between Prot rate and Prot failure stress. This relationship is determined by drawing the line of least squares through the data of Figure 4-24. The intercept of the least squares line with the $\sqrt{\alpha} = 0$ axis gives the endurance limit value of this material.

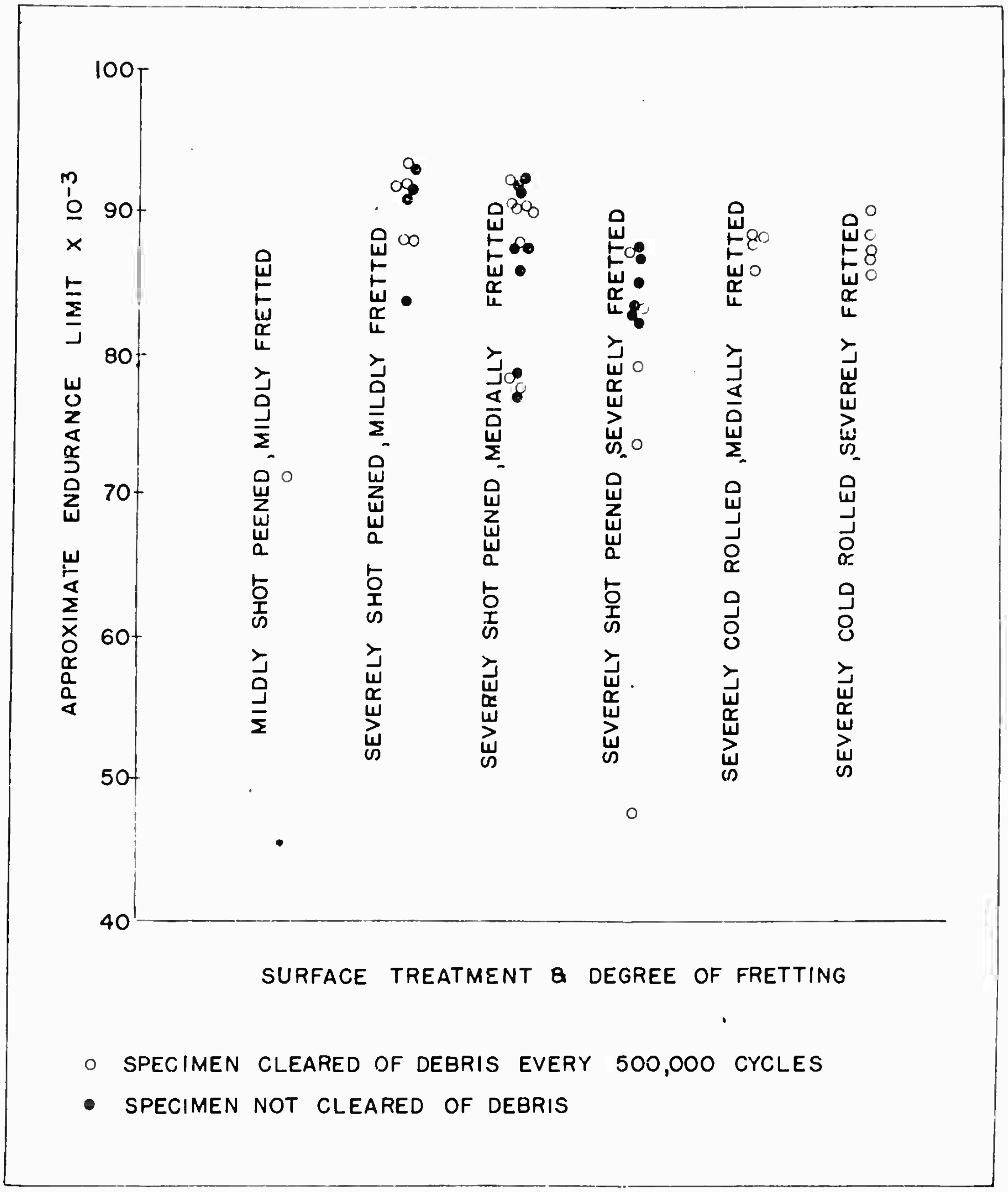
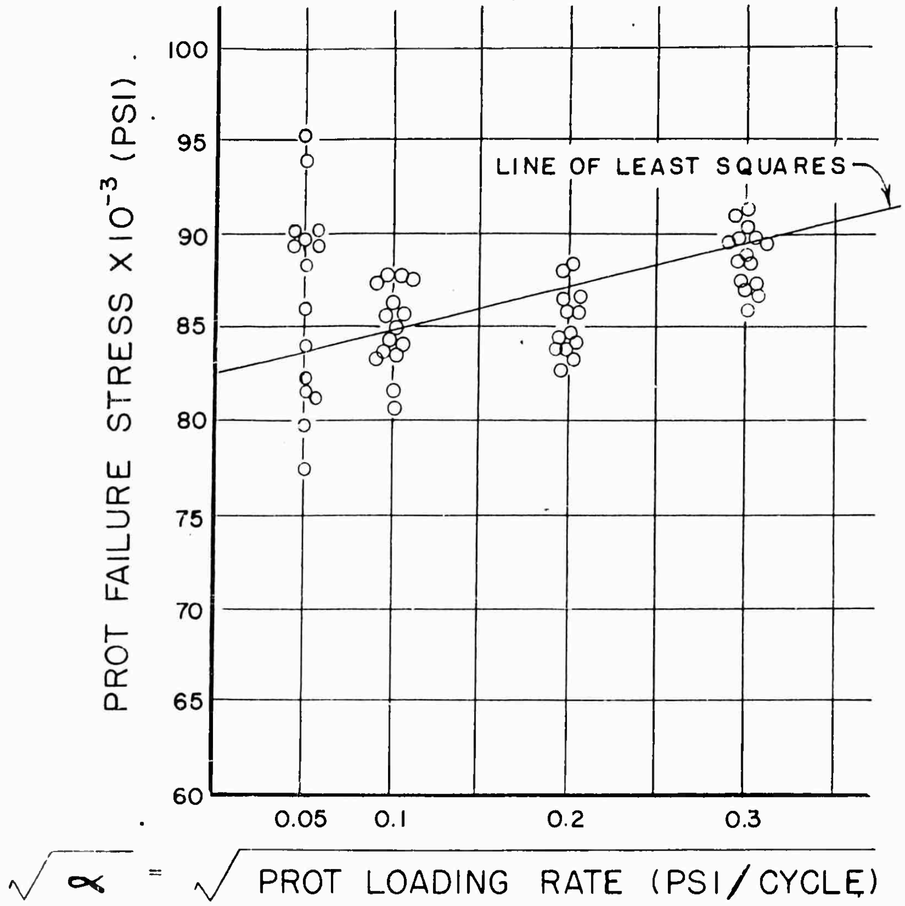


FIGURE 4-23 COMPARISON OF ENDURANCE LIMITS OF TI 140-A TITANIUM SPECIMENS SUBJECTED TO VARIOUS COMBINATIONS OF SURFACE PREPARATION AND FRETTING



$\bar{S}_{.05} = 86{,}500$ PSI $\qquad \bar{S}_{0.1} = 84{,}268$ PSI

$\bar{S}_{0.2} = 85{,}254$ PSI $\qquad \bar{S}_{0.3} = 88{,}537$ PSI

$S_1 = 45{,}000$ PSI (STRESS AT START OF PROT TEST)

FIGURE 4-24 PROT FAILURE STRESS VERSUS THE SQUARE ROOT OF THE PROT RATE USING TI 140-A TITANIUM SPECIMENS AT FOUR DIFFERENT PROT RATES.

For the Prot method of testing, the endurance limit of the Ti-140-A alloy used was found to be 82,600 psi.

To validate the Prot method of testing, a standard up-and-down test was performed on the same material. The results of this test are tabulated in Table B-7 of Appendix B and shown graphically in Figure 4-25. Using the usual method of analysis* for determining 95% confidence limits on the mean endurance limit and the standard deviation, it was found that the mean for the material was 83,200 psi and the standard deviation was 1790 psi. Thus, the up and down test checked the Prot method very closely and the Prot method is valid for the Ti-140-A titanium alloy used in this project.

4.4 TEST 3--COMPARISON OF ENDURANCE LIMITS OF TWO HEATS OF Ti-140-A TITANIUM MATERIAL

Specimens for the research program were made from titanium material taken from two different heats of Ti-140-A alloy. To compare the endurance properties of the two heats, a Prot test was performed on polished, non-fretted, titanium specimens taken from each heat. Thirty specimens were tested from each heat to make this comparison.

The resulting data are presented in Tables B-8 and B-9 of Appendix B. The two heats are compared graphically in Figure 4-26. From these data it may be calculated that the estimated mean endurance limit for the first heat is 79,000 psi with a standard deviation of 3280 psi compared to an estimated mean of 85,900 psi with a standard deviation of 3860 for the second heat.

The means of the two heats are significantly different at the .05 significance level and when data are compared between heats these differences must be taken into account. It should be noted that all specimens from the first heat have been designated by a letter and a number, e.g., A-1, while all specimens from the second heat have been designated by a number 1, a letter, and a number, e.g., 1A-1. This method of specimen identification makes it easy to distinguish between specimens from the two different heats. Chemical analyses and nominal physical properties are shown in Table B-10 of Appendix B for each heat.

4.5 TEST 4--COLLECTION OF SUPPLEMENTORY DATA

Fretting-fatigue research programs** have been performed in which the effects of various surface treatments on fretting-fatigue damage were explored. These investigations consisted of subjecting specimens to surface treatments such as shot-peening or cold-rolling, and then to various degrees of fretting damage.

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* "Proceedings Statical Methods in Materials Research", Pennsylvania State University. Edited by Donald E. Hardenbergh. 1956.

** See reference 1

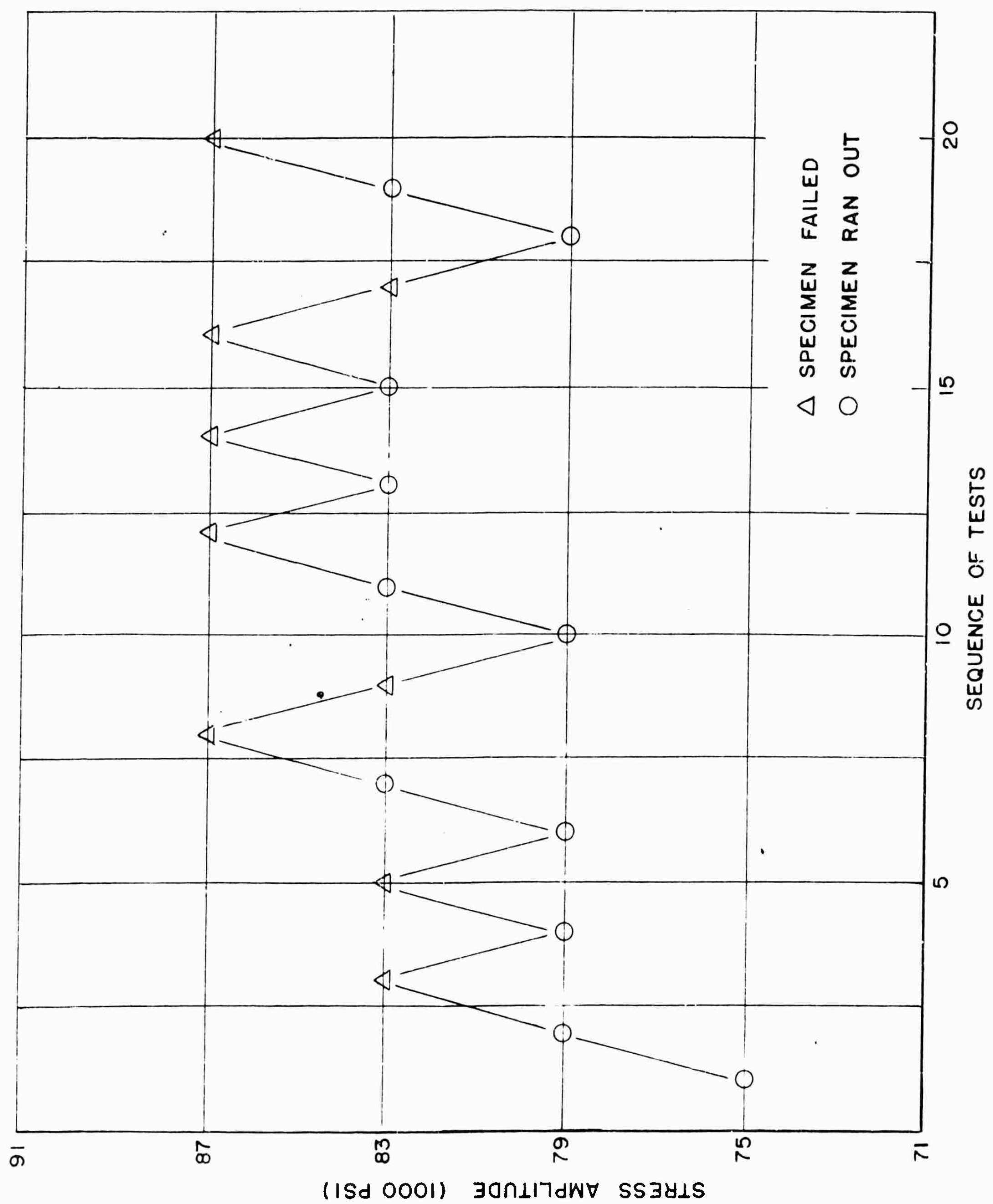

FIGURE 4-25 RESULTS OF "UP & DOWN" TEST USED TO VERIFY PROT ENDURANCE LIMIT

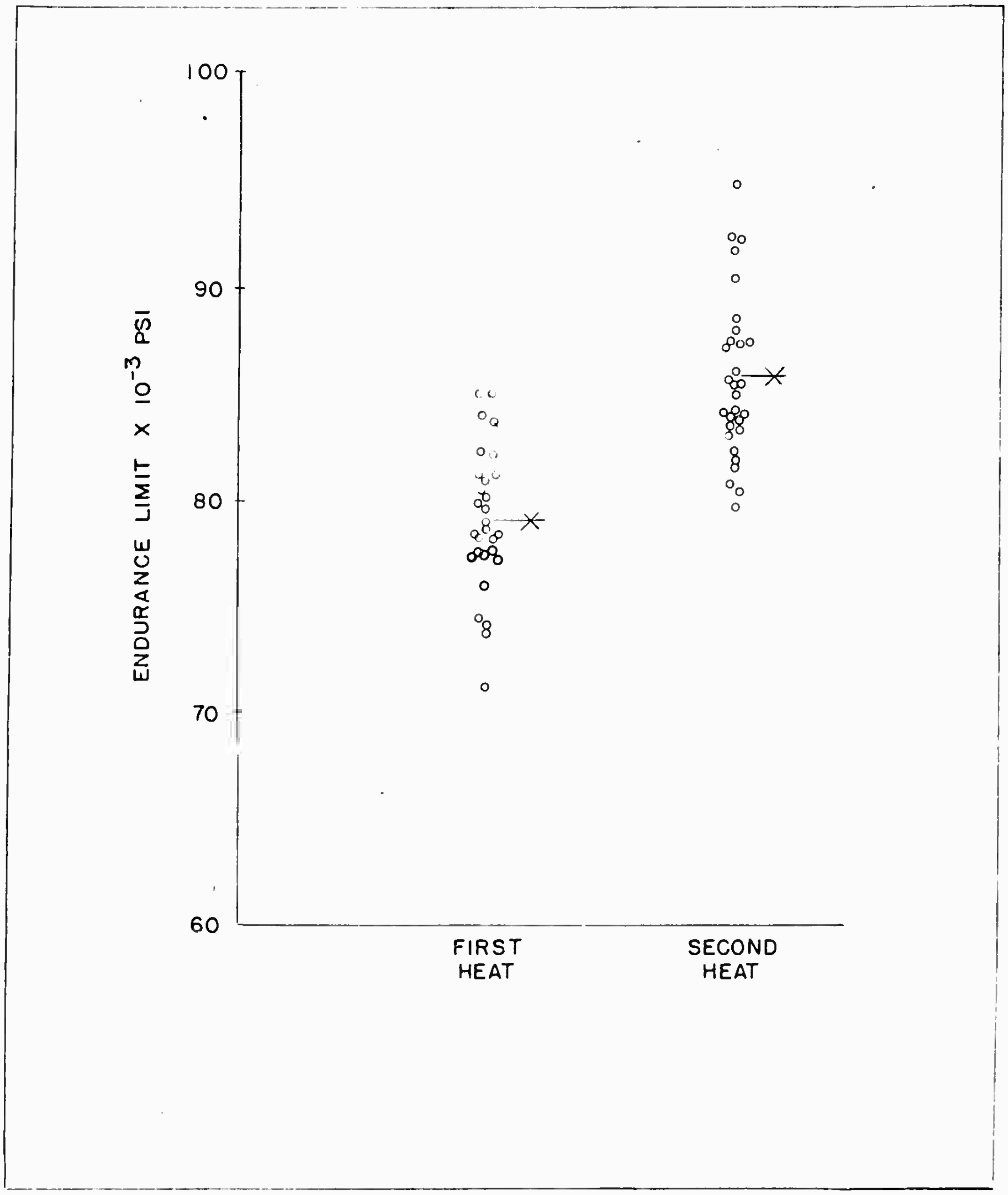

FIGURE 4-26 COMPARISON OF TWO HEATS OF TI 140-A TITANIUM ALLOY HAVING THE SAME NOMINAL COMPOSITION SHOWING THE MEAN AND RANGE OF THE ENDURANCE LIMIT FOR POLISHED NON-FRETTED SPECIMENS FROM EACH HEAT.

Fifteen specimens were fretted at most frequencies with samples of five fretted at the remaining test frequencies.

The results of these tests are shown in Table B-15 of Appendix B and are depicted graphically in Figure 4-28. These results are most interesting. It appears from Figure 4-28 that the endurance limit is definitely a function of fretting speed. In fact, both the mean endurance limit and the scatter appear to be affected by changes in fretting frequency.

Table 4-6 Summary of Data for Polished, Severely Fretted Specimens Fretted at Various Speeds.

Fretting Speed, rpm	No. of Specimens	Mean Endurance Limit, psi	Standard Deviation, psi
100	15	79,850	2,960
500	5	79,900	6,070
750	5	76,040	7,670
1000	5	76,840	16,240
1600	15	63,410	17,136
3000	15	60,330	15,440
4000	15	49,810	17,012
5500	15	63,460	22,790
7200	15	67,060	10,940

Employing F-tests and t-tests at the .05 level of significance to compare the standard deviations and means, one may conclude that fretting speed has a definite effect on endurance limit of these titanium specimens. Further, it may be postulated that at speeds above 7200 rpm the fretting condition may be much less severe than in the 1000-7000 rpm range. Unfortunately, time and equipment limitations prevented further investigations at higher speeds. The problem of speed effect on fretting invites further study and might yield important and useful design information.

4.7 TEST 6—STUDY OF MECHANISM OF FRETTING INHIBITION BY SURFACE TREATMENT

During the course of this exploratory test, the original purpose of studying the mechanism of fretting inhibition by surface treatment has been broadened to a basic study of the fundamental fretting mechanism. The exploration took two general paths, one macroscopic and the other microscopic.

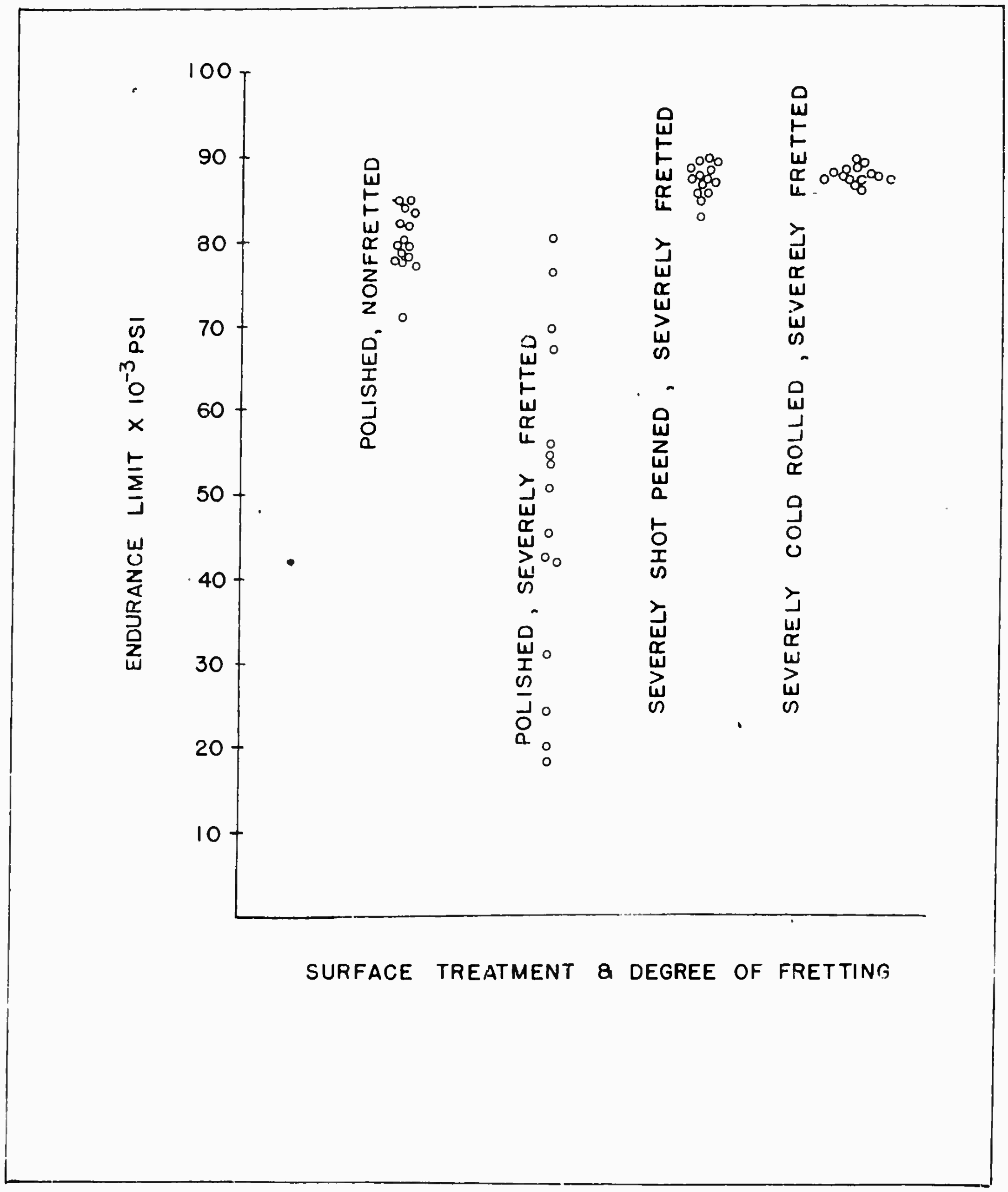

FIGURE 4-27 COMPARISON OF ENDURANCE LIMITS OF TI 140-A TITANIUM SPECIMENS FROM FIRST HEAT SUBJECTED TO VARIOUS COMBINATIONS OF SURFACE PREPARATION AND FRETTING.

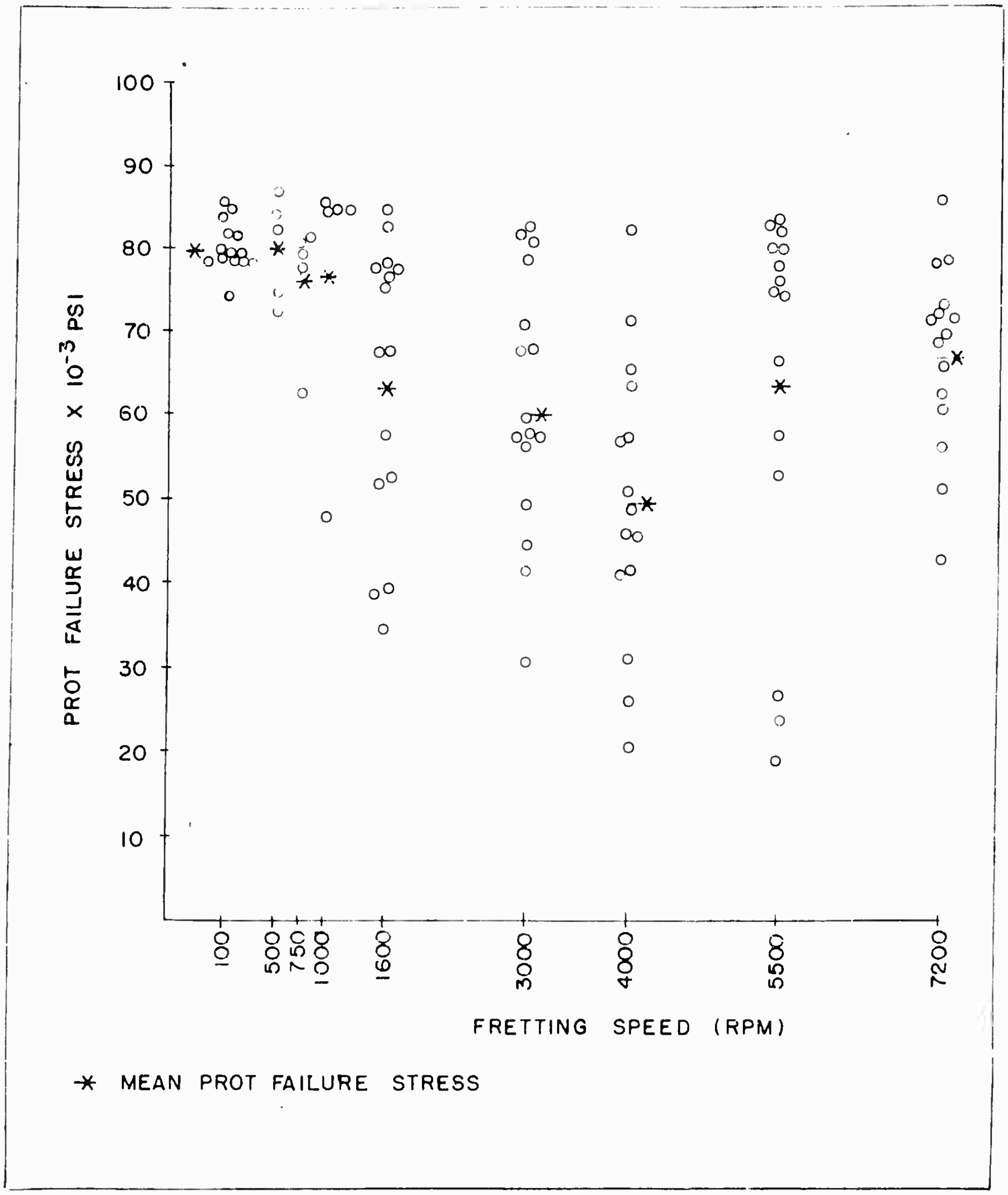

FIGURE 4-28 VARIATION IN PROT FAILURE STRESS OF TI 140-A TITANIUM SPECIMENS FROM SECOND HEAT SUBJECTED TO SEVERE FRETTING AT DIFFERENT FRETTING SPEEDS

The purpose of this test was to select the most promising results from the prior fretting-fatigue exploratory research program and supplement these results with additional data to lend statistical significance to them. The collection of these additional data was limited to four of the most important sets of conditions used in previous tests. These four conditions were defined by the following combinations: (1) polished Ti-140-A titanium specimens subjected to no fretting action, (2) polished Ti-140-A titanium specimens subjected to severe fretting, (3) severely shot-peened Ti-140-A titanium specimens subjected to severe fretting, and (4) severely cold-rolled Ti-140-A titanium specimens subjected to severe fretting. These data are presented in Table B-11, B-12, B-13 and B-14 of Appendix B and are shown graphically in Figure 4-27. The results of these tests are summarized in Table 4-5.

Table 4-5 Summary of Data for Ti-140-A Titanium Specimens Subjected to Various Combinations of Fretting and Surface Preparation.

No. of Specimens	Surface Preparation	Degree of Fretting	Mean Endurance Limit, psi	Standard Deviation, psi
30	Polished	None	79,030	3,280
30	Polished	Severe	44,060	19,870
30	Severely Shot-Peened	Severe	85,380	2,820
30	Severely Cold-Rolled	Severe	90,720	2,720

From these data, it may be concluded that both severe shot-peening and severe cold-rolling are very beneficial in preventing fretting. These treatments increase the mean endurance limit and decrease scatter significantly. This has been shown at the .05 significance level by use of the F-test and t-test using the usual procedures.

4.6 TEST 5--EFFECT OF CYCLIC FRETTING FREQUENCY

The objective of this test was to determine the effect of the frequency of fretting (cycles per minute) on the endurance limit of Ti-140-A titanium specimens. Specimens were fretted at speeds of 100, 500, 750, 1000, 1600, 3000, 4000, 5500 and 7200 cycles per minute.

The macroscopic study involved inspecting and recording certain vital bits of information about each fractured fretting-fatigue specimen. This information included a sketch of the fretted region, classification, size, shape, and orientation of fretted spots related to the fatigue crack causing rupture. These data are all included in this report as Table B-17 of Appendix B. Unfortunately, no significant correlation among any of the measured parameters could be discovered.

The microscopic study, on the other hand, did yield some very interesting information. Specimens were prepared by mechanically polishing the fretted area and making microscopic observations intermittently during the polishing process. Many fatigue cracks were found in the fretted area. From the photomicrographs and the microscopic scanning it was not possible to decide whether fatigue cracks were always initiated in fretted spots, but this was the usual case.

It may be postulated that fretting produces fatigue cracks which initiate in the fretting spots. If the surface of the material is stressed critically, the cracks propagate and ultimately one or more of the cracks result in failure. If the surface layer is shot-peened or cold-rolled, a layer of compressive residual stresses is generated and the fatigue cracks are arrested in growth, causing a great enhancement of endurance properties. This hypothesis is compatible with the results tabulated in Appendix B.

4.8 TEST 7—DESIGN OF WIRE-FRETTING MACHINE

During the exploratory research performed under this contract an hypothesis of fretting action has been developed. This hypothesis postulates that fretting progresses by either or both of two actions — pit digging or asperity contact.

In the pit-digging mechanism, minute debris pockets are formed which lead to pits caused by small oscillatory motion of the abrasive pockets of fretting debris under high local pressure. Pit-digging action probably induces stress concentrations which have their largest dimension parallel to the direction of fretting motion.

In the asperity contact mechanism it is postulated that asperities or protuberances of two mating surfaces in oscillatory contact are caused to strike each other cyclically. This action causes fatigue cracks to initiate at the base of these tiny asperities. These cracks act as stress concentrations which probably have their largest dimensions perpendicular to the direction of fretting motion.

A wire-fretting machine was conceived which would fret wire specimens in two different directions. If the hypothesis described above be true, the wire specimens fretted in the two different directions should exhibit different endurance limits as a result of the difference in orientation of stress concentrations.

A machine to produce fretting in either the longitudinal or circumferential direction was partially designed as shown in Figure 4-29. The sketch shows the mechanism for producing circumferential fretting motion. Use is made of a hydraulic loading mechanism pressing two wire shoes against the wire specimen to produce fretting. The wire specimen is flexure plate supported and eccentrically driven. This system permits independent variation of fretting pressure, amplitude of motion, and speed. The same general scheme would serve to provide longitudinal fretting, but the details have not been completed because the time and funds allotted to this exploratory phase of the program ran out.

4.9 TEST 8--WIRE FRETTING-FATIGUE TESTS

Because the wire fretting machine described in 4.8 was not completed, this test could not be completed either. Progress on this test was limited to the selection of a sample of .187 gauge steel wire specimens which were faced to length in a lathe. The chemical analysis of the wire material was C-.65, Mn-.90, P-.010, S-.027, and Si-.28. The wire was tempered to give an ultimate tensile strength of 221,000 psi. A sample of 21 specimens was tested in Krouse rotating column wire fatigue-testing machines to provide up-and-down data for wire specimens in the non-fretted condition. These control data shown in Figure 4-20 and Table B-16 of Appendix B were necessary to provide a comparison with fretted wire specimens. The up and down data were analyzed in the usual way to yield estimates of 70,000 psi for the mean endurance limit and 2,260 psi for the standard deviation of the selected wire material. Unfortunately, the time and fund limitations prevented completion of this phase of the testing program.

4.10 TEST 9--EXPLORATORY ANALYSIS OF FRETTING-FATIGUE PHENOMENA

This exploration of fretting-fatigue phenomena took two general directions.

One was a continuous search of the literature, which resulted in the file of 82 acticles pertinent to the fretting phenomenon listed in the Bibliography of this report. This was a necessary step to keep abreast of other investigations in the field of fretting so that the work under this contract could proceed without duplication in the most fruitful path.

The second direction of exploration, a development of mathematical fretting analysis, was limited by time, and unfortunately, could not be carried to an immediately useful conclusion. However, the results are presented in the hope that the interest of others may be stimulated to proceed with this work.

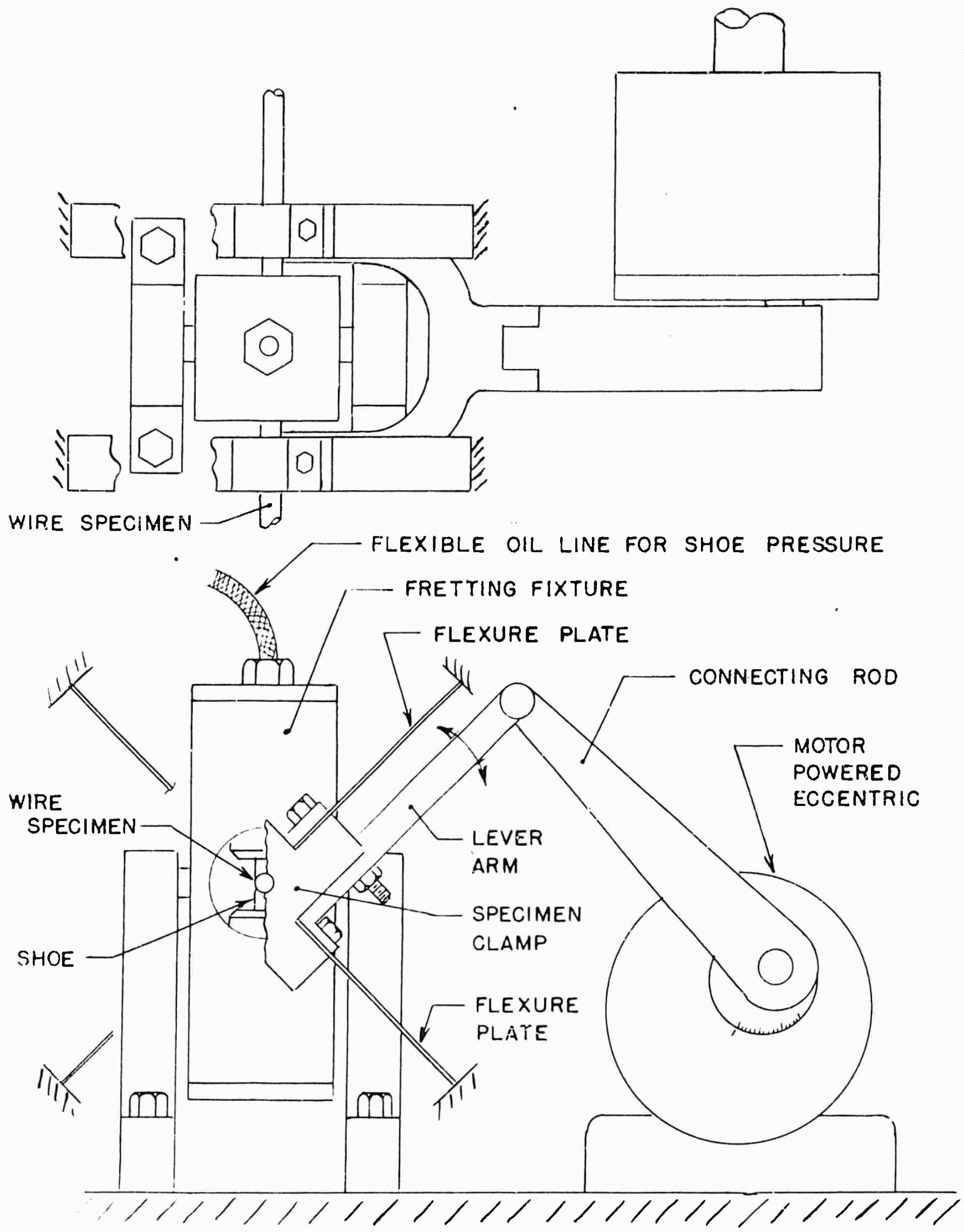

FIGURE 4-29. SCHEMATIC VIEW OF WIRE FRETTING MACHINE.

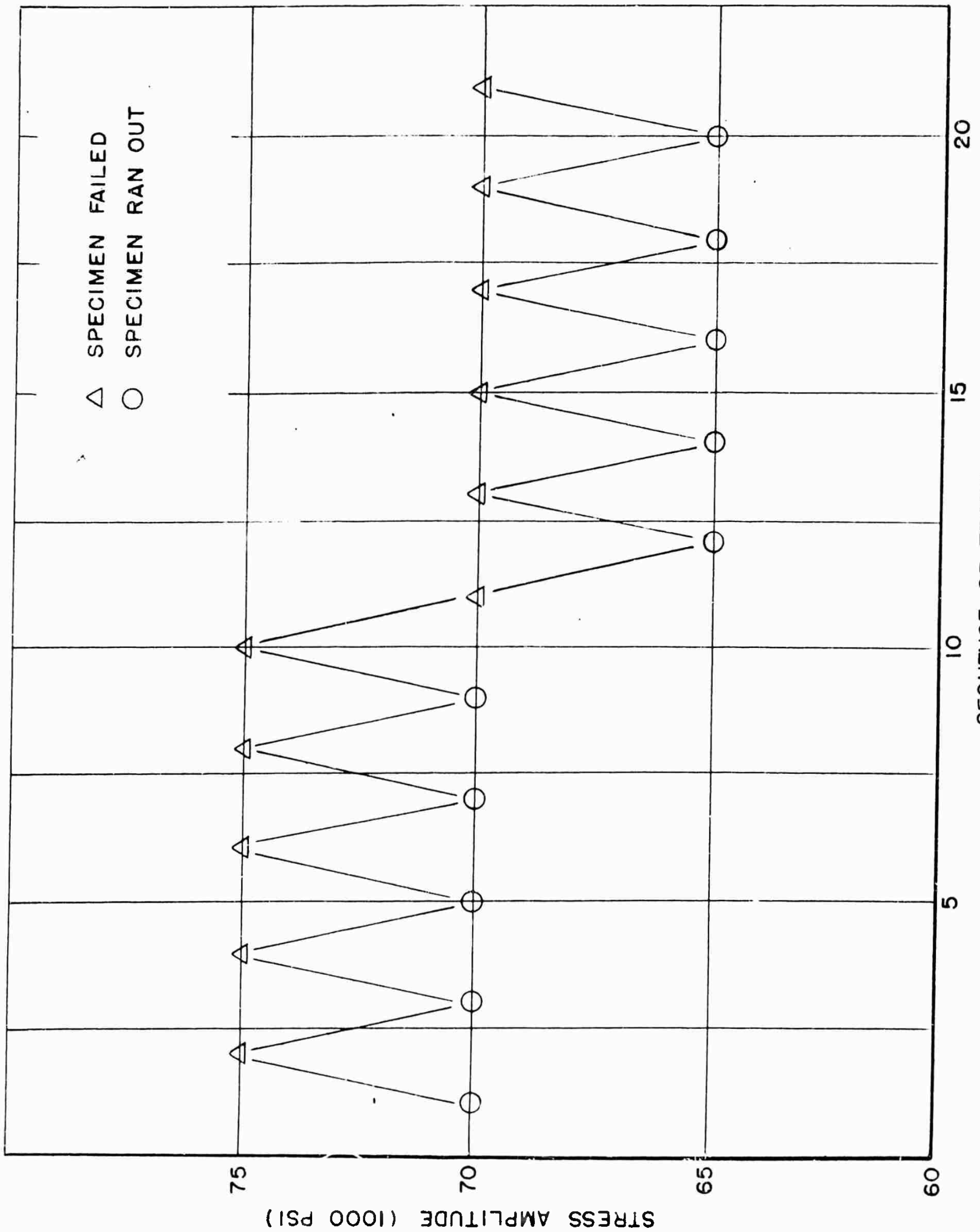

FIGURE 4-30 RESULTS OF "UP & DOWN" TEST USED TO DETERMINE WIRE ENDURANCE LIMIT

The first step in the development of a design equation of this type is to list all variables which might be important in the fretting situation. This list must be combined and modified to yield a shorter list of important variables. Next, the relationships among the variables must be established for "simple" situations and related somehow to easily definable independent variables. Once this has been accomplished, the more complex design situations may be handled by empirical extrapolations based on experiment and superposition. Refinement of the equations based on experience and new research results must then follow.

In beginning this analysis, the variables which may be important are as follows:

1. Materials of the mating parts.
2. Heat treatment of materials.
3. Hardness of materials.
4. Normal and tangential load distribution.
5. Coefficient of friction.
6. Thermal conductivity.
7. Pressure distribution.
8. Magnitude and position of maximum pressure.
9. Relative position of mating parts in the electromotive series.
10. Chemical reactivity and combinativity.
11. Ambient atmospheric composition.
12. Humidity.
13. Ambient temperature.
14. Interface temperature.
15. Ability of materials to form oxides.
16. Size of oxide particles.
17. Shape of oxide particles.
18. Hardness of oxide particles.
19. Weldability of the combination of materials.
20. Melting temperatures of materials.
21. Recrystallization temperatures of materials.
22. Recovery rates of materials.
23. Amplitude of motion.
24. Direction of motion, especially with respect to stress field.
25. Cyclic form of motion pattern.
26. Magnitude, direction, and type of applied stress field.
27. Magnitude, direction, and type of residual stress field due to heat treatment, shot-peening, cold-rolling, or other treatment.
28. Surface roughness or waviness.
29. Notch sensitivity.
30. Fracture strengths of materials.
31. Flow stress or yield stress.
32. Endurance limit stress.
33. Modulii of elasticity of materials.
34. Type of forming or machining process used to fabricate parts.
35. Directions and types of surface markings.
36. Stability of the oxide.
37. Wear properties.
38. Geometry of the mating parts.

39. Size of the contact area.
40. Type of fit at contact area, i.e., press fit, loose fit, etc.
41. Speed of oscillation.
42. Continuous or intermittent service.
43. Dry, lubricated, or contaminated mating surfaces.
44. Weight change or rate of weight change during fretting.
45. Dimensional change or rate of dimensional change during fretting.
46. Change or rate of change of contact area.
47. Damping capacity of materials.
48. Natural vibration characteristics of parts involved.
49. Self excited vibration due to stick-slip action.
50. Nominal contact stress.
51. Poisson's ratio effects.
52. Ductility and malleability of materials involved.
53. Time or duration of fretting contact.
54. Depth of residual stress field.
55. Crystal lattice structure of materials.

This list may not exhaust all possibilities but most of the variables known today are included. The job of developing design equations from this beginning has not been undertaken because of time limitations. Future research along these lines would provide a real contribution to the solution of the fretting problem.

Investigator Jack A. Collins Date 5-26-58

Supervisor [illegible] Date [illegible]

For The Ohio State University Research Foundation

Executive Director Oran C. Woolpert Date 5/27/58

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APPENDIX A

BACKGROUND

Serious conditions of cyclic loading frequently exist at the hubs of aircraft-propeller assemblies. It is also true that some parts of the hub are assembled with interference fits between mating surfaces. For example, the fit between the propeller shank and the bearing race with which it mates is an interference fit. Because of the geometry of the mating parts and the loads to which they are subjected, differential strains often occur. These differential strains manifest themselves as relative motions between tightly fitting mating surfaces. This combination of conditions results in the simultaneous occurrence of biaxial cyclic stressing and surface fretting.

When two solid bodies are forced together under normal pressure, only the high spots, often called asperities, actually come into contact. The actual area of contact is sufficiently small that stresses exceeding the yield point of one or both substances are induced at the contacting asperities by small nominal surface pressure. If fretting conditions are present, tangential forces will cause tangential slip which will also cause yielding at contacting asperities. If the fretting is occurring in air, the surfaces of the asperities will probably be coated with chemical compounds involving the constituents of the metal and the constituents of air, usually metallic oxides. If, in addition, contaminants, including lubricants, are interposed between the surfaces, it is likely that chemical compounds involving the constituents of the contaminants will also be present. As the normal and tangential forces cause the asperities and the associated chemical coatings to be forced together under high local stresses in the early stages of fretting, one or a combination of several mechanical, chemical, thermal, and probably other phenomena result.

1. Contacting asperities plow through each other to cause plastic deformation, possibly producing rough-edged furrows, loose particles, or particles still attached but nearly dislodged as loose particles.

2. Contacting asperities plastically deform each other and form a mechanical interlock by the production of mating jagged surfaces through slip at corresponding slip planes of the two surfaces.

3. Contacting asperities weld together through the influence of high pressure and raised temperature accompanying plastic deformation.

4. Asperities dislodge free metallic particles by further deforming the furrows of previous plowing.

5. Asperities produce free metallic particles by shearing off the roots of previously mechanically interlocked asperities.

6. Asperities produce free metallic particles by rupturing previously welded asperities.

7. Free or incipiently dislodged metallic particles are reattached by welding to one or the other surface under the influence of pressure and temperature.

8. Chemical reactions involving particles, surfaces, contaminants, or atmosphere are catalyzed through the influence of pressure, temperature, and stress.

9. Chemical reactions involving particles, surfaces, contaminants or atmosphere are permitted to occur spontaneously by mechanical removal of chemically protective coatings.

10. Chemical reactions are induced by forming fine particles or jagged edged furrows having a large ratio of surface to volume.

11. Adsorption of atmosphere or contaminant by particles or surface occurs.

12. Products of chemical reactions are mechanically embedded in one or the other surface by pressure.

13. Products of chemical reactions attached to one or the other surface are removed to form chemically combined particles either by plowing or by mechanical interlock mechanisms.

Which of the above phenomena predominate depends upon the conditions of fretting and the substances involved. Unless the action is entirely metal transfer or is self-limiting through the production of protective coatings, the surfaces will be damaged by such fretting corrosion or fretting wear.

As fretting proceeds beyond the initial stage, additional mechanisms become important. In practical applications, fretting usually proceeds in the presence of air and the primary particles produced are metallic oxides. If these oxides are soft and have low shear resistance they may act as solid lubricants. On the other hand, if they are hard and abrasive, and especially if their volume is greater than that of the pure metal from which they were formed, they will begin to dig pits into the surface of the parent metals. Under fretting conditions much of the debris is trapped in the valleys below the asperities. If some debris does escape it must do so in accordance with the laws governing the flow of a granular mass which suggests that high flow pressures are induced as the high volume debris is generated. All of these conditions, together with the cyclic relative motion of the bounding surfaces, manifestly are conducive to pit-forming abrasive action. Such pits add to the surface damage and contribute to corrosion and wear. In addition, such pits undoubtedly act as stress raisers and tend to initiate fatigue cracks.

Also as fretting proceeds another significant phenomenon is probably active. The state of stress induced in an asperity, and in the region around the asperity, when contact occurs with an asperity of the opposite surface, undoubtedly involves principal stresses of high value. If a particular asperity continues to survive under repeated contacts with one or more mating asperities of the opposite surface, it is apparent that it and its surrounding metallic support are subjected to high-level fatigue stressing. Indeed, Corten has submitted evidence which seems to indicate that such stresses may be much larger than the nominal stresses in machine parts under typical conditions of fretting. This high local stress of a cyclic nature may be largely responsible for the fact that under fretting conditions fatigue cracks will be initiated at extremely low nominal stresses.

It may be conjectured that the stress raisers due to pit-digging, the high, local, cyclic stresses due to asperity contacts, and the cyclic nominal stresses in the part, all combine their influences to initiate and propagate fatigue cracks. Which particular influence predominates probably also depends upon the condition of fretting and the substances involved.

A research project was initiated to simulate in the laboratory the conditions of cyclic stressing and surface fretting described above. It was the purpose of this project to discover the effects of fretting on the fatigue characteristics of the material involved. To this end, an experimental testing program was planned. The broad objectives of the testing program were (1) to study the fatigue characteristics of fretted Ti-140-A titanium alloy specimens, (2) to study the fatigue characteristics of fretted 4340 steel specimens (these tests were to provide data with which to compare the results of the titanium tests), and (3) to apply various surface treatments or combinations of surface treatments to groups of titanium specimens to determine the effects of such treatments on the fretting-fatigue characteristics of the alloy tested. A series of tests was designed to fulfill each of the objectives.

More than twenty different sets of test conditions were used. These conditions embraced two different materials, three different degress of fretting, various ratios of fretting pressure to applied bending stress, three different types of specimen surface preparation, and combinations of these conditions. The two materials were SAE 4340 steel and Ti-140-A titanium alloy. The three types of surface preparation consisted of polished, shot-peened, and cold-rolled surfaces. The three degrees of fretting — mild, medium and severe — were a function of the fretting pressures used.

It was found that the titanium alloy tested was more sensitive to fretting-fatigue damage than the steel alloy tested. For both materials it was shown that as the severity of fretting is increased, the mean endurance limit is lowered and the scatter increased greatly. It was further noted that a decrease in endurance limit occurs when either the fretting pressure or number of fretting cycles is increased. With the fretting pressure and number of fretting cycles held constant, it was observed that an increase in cyclic stress amplitude during the fretting process resulted in a marked decrease in the endurance limit. Both shot-peening and cold-rolling are effective as fretting fatigue inhibitors. At a testing speed of 4,000 rpm it was found that changes in relative humidity had little effect on the fretted endurance limit; thus, at this speed the fretting action would appear to be primarily mechanical in nature with the chemical action contributing only a small part of the damage.

The results of the testing program described above led to many interesting questions. To answer some of these questions the current research program was initiated. A summary of test results of the current program is given in Section IV in the body of this report.

APPENDIX B

MATERIALS DATA SECTION

This section includes all data accumulated on the project. Symbols used in the table headings are defined as follows:

E	endurance limit, psi.
M	mild treatment.
Me	medium treatment.
MCR	mild cold-rolling.
MSP	mild shot-peening.
N_{fr}	number of cycles of fretting.
P	polished surface.
S	severe treatment.
SCR	severe cold-rolling.
SSP	severe shot-peening.
S_{α}	Prot failure stress, psi.
W/L	ratio of widthto length of the fretting spot in which the fatigue fracture appeared to initiate.
α	Prot loading rate, psi/cycle.
β	angle between major axis of fretting spot in which fatigue fracture initiated and the longitudinal specimen axis, degrees.
θ	angle between plane of fracture at position where fatigue fracture initiated and the longitudinal specimen axis, degrees.
$[\ \ ]_{N(\ \ )}$	fretting treatment modified by altering the number of fretting cycles to ( ).
$[\ \ ]_{S(\ \ )}$	fretting treatment modified by altering the fretting speed to ( ) rpm.
$\odot$	position of the region in which fatigue fracture initiated.

Table B-1. Values of Parameters Defining Two Degrees of Shot-Peening

PARAMETER	MILD SHOT-PEENING	SEVERE SHOT-PEENING
Nozzle diameter, in.	0.25	0.25
Nozzle air pressure, psi.	20.00	40.00
Nozzle gap, in.	6.00	2.00
Shot size diam., in.	0.033	0.033
Weight rate of shot flow, lb/min.	8.12	9.09
Per cent of coverage	100+	100+
Velocity of nozzle relative to specimen, in/sec.	1.00	1.00
Number of passes	8.00	16.00
Almen "A" strip intensity height, in.	0.0188	0.0295
Almen "C" strip intensity height, in.	0.1050	0.0075

Table B-2. Values of Parameters Defining Two Degrees of Cold-Rolling

PARAMETER	MILD COLD-ROLLING	SEVERE COLD-ROLLING
Spring load, lb.	35	100
Roller load, lb.	525	1500
Number of passes	One (toward head of stock of lathe	One (toward head of stock of lathe)
Specimen rotative speed, RPM	9	9
Translational feed of cold-rolling fixture, in/rev.	0.009	0.009
Maximum roller diam., in.	2.00	2.00
Contour radius of roller, in.	0.750	0.750
Spring Dimensions, in.	2.02 O. D. 1.2 I. D.	2.02 O. D. 1.2 I. D.
Spring scale, lb./in.	112	112
Minimum specimen diameter, in.	0.375 (nominal)	0.375 (nominal)
Lubrication	Constant flow of Bardahl E. P. Lubricant	Constant flow of Bardahl E. P. Lubricant

Table B-3. Values of Parameters Defining Three Degrees of Fretting

PARAMETER	MILD FRETTING	MEDIUM FRETTING	SEVERE FRETTING
Fretting moment, in-lb.	50	100	150
Specimen sweep radius, in.	2.868	2.868	2.868
Nominal specimen contours radius, in.	0.3750	0.3750	0.3750
Fretting shoe sweep radius, in.	2.468	2.468	2.468
Nominal fretting shoe contour radius, in.	0.3755	0.3755	0.3755
Range of permissible clearance between maximum specimen contour diameter and minimum fretting shoe contour diameter, in.	0.0005-0.0010	0.0005-0.0010	0.0005-0.0010

Table No. B-4. Results of Exploratory Fretting Tests of Ti-140-A Titanium Specimens Subjected to Various Surface Treatments and Degrees of Fretting Under Conditions of Large Numbers of Fretting Cycles at a Fretting Speed of 4000 rpm and Prot rate of 0.01 psi Per Cycle.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} $\times 10^{-3}$	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress $\times 10^{-3}$, psi	Endurance limit, $\times 10^{-3}$, psi
Severly Shot-Peened Mildly Fretted	1-B-3	486	0	.37540	.37609	163.5210	62.5280		
			500	.37531	.37531	163.5210	62.5280		
			1,000	.37533	.37594	163.5271	62.5598		
			1,500	.37502	.37600	163.5185	62.5549		
			2,000	.37468	.37617	163.5200	62.5578		
			2,500	.37476	.37629	163.5163	62.5570		
			3,000	.37418	.37591	163.5105	62.5549		
			3,500	.37407	.37517	163.5100	62.5547		
			4,000	.37359	.37618	163.5065	62.5564		
			4,500	.37348	.37609	163.5025	62.5535		
			5,000	.37284	.37621	163.4995	62.5532		
			5,500	.37247	.37638	163.4970	62.5525		
			6,000	.37259	------	--------	-------	89.8	88.1
Severely Shot-Peened Mildly Fretted	1-H-12	604		.37476	.37593	--------	-------		
			500	.37361	.37556	163.7595	62.4160		
			1,000	.37348	.37552	163.7525	62.4190		
			1,500	.37278	.37563	163.7490	62.4200		
			2,000	.37208	.37595	163.7450	62.4188		
			2,500	.37133	.37615	163.7432	62.4185		
			3,000	------	------	163.7370	62.4178	89.9	88.3

Table No. B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Mildly Fretted	1-N-9	741	0	.37452	.37598	162.837	63.163		
			500	.37336	.37565	162.835	63.162		
			1,000	.37285	.37592	162.832	63.161		
			1,500	.37197	.37623	162.830	63.159		
			2,000	.37160	.37653	162.827	63.155		
			2,214	.37128	.37681	162.824	63.153	93.8	92.1
Severely Shot-Peened Mildly Fretted	1-N-14	868	0	.37393	.37471	164.021	64.387		
			500	.37360	.37453	164.018	64.384		
			1,000	.37332	.37456	164.016	64.384		
			1,500	.37314	.37435	164.015	64.382		
			2,000	.37278	.37477	164.013	64.383		
			2,500	.37244	.37453	164.011	64.382		
			3,000	.37219	.37470	164.009	64.382		
			3,500	.37193	.37463	164.006	64.381		
			4,000	.37153	.37513	164.004	64.379		
			4,500	.37119	.37402	164.003	64.379		
			5,000	.37081	.37530	164.000	64.374		
			5,500	.37048	.37545	163.999	64.373		
			6,000	.37039	.37575	163.996	64.370		
			6,500	.37004	.37618	163.994	64.366		
			7,000	.36970	.37624	163.990	64.365		
			7,300	.36936	.37613	163.987	64.363	95.2	93.5

Table No. B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Mildly Fretted	1-N-20	782	0	.37642	.37743	162.056	63.418		
			500	.37629	.37724	162.055	63.416		
			1,000	.37585	.37719	162.055	63.417		
			1,500	.37553	.37698	162.054	63.416		
			2,000	.37518	.37712	162.050	63.415		
			2,500	.37475	.37714	162.048	63.415		
			3,000	.37413	.37736	162.047	63.414		
			3,500	.37384	.37771	162.043	63.411	93.6	91.9
Severely Shot-Peened Medially Fretted	1-C-25	722	0	.37443	.37537	164.327	63.233		
			500	.37386	.37508	164.325	63.233		
			1,000	.37312	.37499	164.324	63.233		
			1,500	.37195	.37522	164.313	63.227		
			2,000	.37153	.37576	164.306	63.222		
			2,500	.36988	.37673	164.300	63.213		
			3,000	.36865	.37766	164.291	63.199		
			3,200	.36792	.37823	164.284	63.197	94.1	92.4
Severely Shot-Peened Medially Fretted	1-N-10	831	0	.37526	.37612	161.920	64.265		
			500	.37514	.37577	161.915	64.264		
			1,000	.37480	.37552	161.915	64.260		
			1,500	.37466	.37585	161.913	64.265		
			2,000	.37433	.37544	161.912	64.261		
			2,500	.37404	.37561	161.906	64.258		
			3,000	.37356	.37589	161.904	64.265		
			3,500	.37316	.37595	161.900	64.259		
			4,000	.37246	.37634	161.897	64.250		

Table B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Medially Fretted	1-N-10	831	4,500	.37232	.37696	161.895	64.242		
			5,000	.37106	.37760	161.888	64.239	92.1	90.5
Severely Shot-Peened Medially Fretted	1-N-5	801	0	.37484	.37540	162.580	64.325		
			500	.37402	.37522	162.579	64.323		
			1,000	.37333	.37510	162.575	64.322		
			1,500	.37280	.37522	162.571	64.321		
			2,000	.37233	.37540	162.568	64.316		
			2,500	.37201	.37650	162.563	64.313		
			3,000	.37156	.37610	162.558	64.308		
			3,500	.37061	.37597	162.553	64.305		
			4,000	.37057	.37684	162.545	64.298		
			4,500	.36905	.37768	162.536	64.287	92.2	90.5
Severely Shot-Peened Medially Fretted	1-K-19	811	0	.37510	.37580	163.846	64.417		
			500	.37488	.37526	163.845	64.418		
			1,000	.37456	.37528	163.845	64.416		
			1,500	.37423	.37543	163.839	64.415		
			2,000	.37380	.37534	163.837	64.416		
			2,500	.37348	.37573	163.835	64.411		
			3,000	.37322	.37582	163.830	64.408		
			3,500	.37268	.37632	163.826	64.402		

Table No. B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Medially Fretted	1-K-19	811	4,000	.37225	.37668	163.822	64.397		
			4,500	.37166	.37713	163.817	64.392		
			5,000	.37033	.37769	163.805	64.381		
			5,500	.36809	------	163.794	64.366	91.9	90.2
Severely Shot-Peened Medially Fretted	1-N-15	830	0	.37500	.37598	163.277	64.295		
			500	.37438	.37571	163.272	64.296		
			1,000	.37334	.37578	163.270	64.292		
			1,500	.37288	.37642	163.266	64.287		
			2,000	.37244	.37639	163.262	64.281		
			2,500	.37192	.37724	163.257	64.274		
			3,000	.37164	.37779	163.253	64.265		
			3,500	.37098	.37892	163.246	64.255		
			3,840	.37029	.37949	163.239	64.246	92.3	90.6
Severely Shot-Peened Medially Fretted	1-D-2	827-	0	.37513	.37658	162.922	63.916		
			500	.37453	.37585	162.919	63.914		
			1,000	.37406	.37566	162.918	63.914		
			1,500	.37368	.37628	162.915	63.914		
			2,000	------	------	--------	------		
			2,500	.37304	.37579	162.910	63.913		
			3,000	.37252	.37640	162.906	63.910		
			3,500	.27200	.37634	162.901	63.908		
			4,000	.37150	.37659	162.897	63.905		
			4,500	.37040	.37703	162.893	63.903		
			5,000	.36880	.37784	162.887	63.895		
			5,500	.36842	.37860	162.875	63.879	79.5	77.9

Table B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} $\times 10^{-3}$	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress $\times 10^{-3}$, psi	Endurance Limit, $\times 10^{-3}$, psi
Severely Shot-Peened Medially Fretted	1-P-22	715	0	.37475	.37596	163.615	63.409		
			500	.37248	.37567	163.608	63.406		
			1,000	.37158	.37692	163.599	63.403		
			1,500	.37031	.37694	163,591	63.398		
Severely Shot-Peened Medially Fretted	1-P-20	845	0	.37486	.37652	161.560	63.847		
			500	.37339	.37586	161.555	63.845		
			1,000	.37254	.37650	161.549	63.841		
			1,500	.37170	.37631	161.542	63.839		
			2,000	.37077	.37679	161.537	63.835		
			2,500	.36937	.37740	161.529	63.830		
			3,000	.36761	.37861	161.514	63.813		
			3,500	.36449	.38332	161.395	63.805	89.9	88.2
Severely Shot-Peened Medially Fretted	1-H-17	805	500	.37514	.37669	162.394	63.850		
			1,000	.37467	.37615	162.389	63.849		
			1,500	.37371	.37633	162.384	63.847		
			2,000	.37339	.37695	162.377	63.846		
			2,500	.37232	.37663	162.371	63.844		
			3,000	.37178	.37681	162.364	63.842		
			3,500	.37013	.37758	162.357	63.838		
			4,000	.36870	.37790	162.354	63.829		
			4,500	.36736	.37862	162.330	63.817	80.1	78.4

Table No. B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Severely Fretted	1-C-6	686	0	.37453	.37568	162.8515	63.3650		
			500	.37328	.37507	162.8395	63.3630		
			1,000	.37086	.37548	162.8225	63.3590		
			1,500	.36825	.37860	162.8063	63.3315		
			1,600	.36333	------	162.7648	63.2855	75.6	73.9
Severely Shot-Peened Severely Fretted	1-C-19	666	0	.37451	.37554	162.5934	63.7380		
			500	.37298	.37495	162.5825	63.7363		
			1,000	.37071	.37535	162.5670	63.7305		
			1,500	.36792	.37775	162.5515	63.7035		
			1,600	------	------	162.5351	63.6841	81.0	79.3
Severely Shot-Peened Severely Fretted	1-C-20	633	0	.37424	.37509	162.7366	63.6486		
			500	.37403	.37458	162.7399	63.6466		
			1,000	.37281	.37433	162.7334	63.6450		
			1,500	.37175	.37470	162.7255	63.6425		
			2,000	.36983	.37522	162.7115	63.6425		
			2,500	.36779	.37773	162.6986	63.6099		
			2,700	------	------	162.5675	63.4422	49.8	49.1

Table No. B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} $\times 10^{-3}$	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress $\times 10^{-3}$, psi	Endurance Limit, $\times 10^{-3}$, psi
Severly Shot-Peened Severely Fretted	1-C-11	638	0	.37429	.37562	162.9322	63.0168		
			500	.37287	.37498	162.9209	63.0150		
			1,000	.37091	.37537	162.9075	63.0105		
			1,500	.36888	.37618	162.8942	63.0006		
			1,750	.36685	.37862	162.8803	62.9685	85.0	83.3
Severely Shot-Peened Severely Fretted	1-C-13	619	0	.37433	.37546	162.9212	63.4726		
			500	.37295	.37468	162.9012	63.4605		
			1,000	.37058	.37520	162.8962	63.4562		
			1,500	.36804	.37655	162.8817	63.4430	88.9	87.3
Severely Coll-Rolled Severely Fretted	1-B-26	670	0	.37493	.37608	163.4535	63.6350		
			500	.37477	.37541	163.4490	63.6327		
			1,000	.37406	.37576	163.4465	63.6295		
			1,500	.37301	.37703	163.4375	63.6193		
			2,000	.37156	.37865	163.4265	63.6030		
			2,500	.36919	———	163.4078	63.5465	88.4	86.8
Severely Cold-Rolled Severely Fretted	1-H-20	608	0	.37380	.37488	162.5052	63.2220		
			500	.37264	.37489	162.4998	63.2192		
			1,000	.37121	.37523	162.4910	63.2135		
			1,500	.37002	.37661	162.4820	63.2000		
			1,800	.36891	———	162.4720	63.1832	89.1	87.4

Table No. B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely	1-H-22	648	0	.37415	.37545	162.5800	63.4580		
Cold-Rolled			500	.37358	.37525	162.5760	63.4545		
Severely			1,000	.37224	.37616	162.5675	63.4427		
Fretted			1,500	.37128	.37816	162.5615	63.4250	91.9	90.2
Severely	1-B-12	676	0	.37436	.37576	163.0545	63.6905		
Cold-Rolled			500	.37391	.37557	163.0497	63.6874		
Severely			1,000	.37265	.37618	163.0415	63.6815		
Fretted			1,500	.37110	.37783	163.0336	63.6605	90.3	88.6
Severely	1-B-13	549	0	.37420	.37530	162.7785	62.8717		
Cold-Rolled			500	.37415	.37450	162.7725	62.8710		
Severely			1,000	.37409	.37481	162.7707	62.8695		
Fretted			1,500	.37384	.37450	162.7685	62.8697		
			2,000	.37327	.37487	162.7647	62.8679		
			2,500	.37177	.37520	162.7545	62.8635		
			3,000	.37014	.37727	162.7457	62.8432		
			3,500	.36817	———	162.7295	62.8050	87.4	85.8
Severely	1-B-22	620	0	.37452	.37533	111.318	63.599		
Cold-Rolled			500	.37448	.37605	111.315	63.597		
Medially			1,000	.37451	.37677	111.315	63.593		
Fretted			1,500	.37438	.37632	111.307	63.593		
			2,000	.37433	.37640	111.306	63.600		
			2,500	.37400	.37672	111.300	63.597		

Table No. B-4, continued.

Surface Treatment and Degree of Fretting	Specimen No.	Shoe No.	N_{fr} $\times 10^{-3}$	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress $\times 10^{-3}$, psi	Endurance Limit, $\times 10^{-3}$, psi
Severely Cold-Rolled Medially Fretted	1-B-22	620	3,000	.37362	.37660	111.298	63.598		
			3,500	.37291	.37668	111.294	63.598		
			4,000	.37247	.37688	111.290	63.596		
			4,500	.37122	.37698	111.282	63.595		
			5,000	.37048	.37705	111.274	63.588		
			5,500	.36900	———	111.261	63.577	89.9	88.3
Severely Cold-Rolled Medially Fretted	1-B-23	678	0	.37434	.37536	111.496	63.611		
			500	.37443	.37672	111.496	63.611		
			1,000	.37435	.37695	111.489	63.610		
			1,500	.37431	.37607	111.494	63.609		
			2,000	.37408	.37615	111.4[illegible]	63.610		
			2,500	———	———	111.479	63.605		
			3,000	.37353	.37620	111.477	63.606		
			3,500	.37313	.37660	111.473	63.607		
			4,000	.37221	.37718	111.463	63.600		
			4,500	.37330	.37862	111.282	63.595		
			5,000	.37048	.37788	111.274	63.588		
			5,500	.36870	———	111.261	63.577	90.3	88.6

Table No. B-5. Comparison of Severely Shot-Peened Specimen-Shoe Joints Fretted Continuously for Several Million Cycles With Severely Shot-Peened Specimen-Shoe Joints Disassembled and Cleaned Each 500,000 Cycles During Several Million Cycles.

NOTE: A = Specimen and Shoe Fretted Without Disassembly During Entire Run.
B = Specimen and Shoe Disassembled and Cleaned After Each 500,000 Cycles.

Surface Treatment and Degree of Fretting	Testing Condition (See Note)	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Severely Fretted	B	1-C-6	686	0	.37453	.37568	162.8515	63.3350		
				1,500	.36825	.37860	162.8063	63.3315	75.6	73.9
	B	1-C-19	666	0	.37451	.37554	162.5934	63.7380		
				1,500	.36792	.37775	162.5515	63.7035	81.0	79.3
	B	1-C-20	633	0	.37424	.37509	162.7366	63.6486		
				2,500	.36779	.37773	162.6986	63.6099	49.8	49.1
	B	1-C-11	638	0	.37429	.37562	162.9322	63.0168		
				1,750	.36685	.37862	162.8803	63.9685	85.0	83.3
	B	1-C-13	619	0	.37433	.37546	162.9212	63.4726		
				1,500	.36804	.37655	162.8817	63.4430	88.9	87.3
Severely Shot-Peened Severely Fretted	A	1-P-5	849	0	.37402	.37534	163.035	63.922		
				3,000	.36916	.37498	163.004	63.904	86.9	85.2
	A	1-P-8	828	0	.37499	.37593	163.167	63.633		
				2,763	.36786	.37884	163.117	63.587	85.1	83.4
	A	1-P-9	814	0	.37410	.37495	164.018	64.490		
				3,000	.37011	.37543	163.988	64.477	89.5	87.9
	A	1-P-11	661	0	.37495	.37623	163.645	62.033		
				931	.36939	.37208	163.616	62.000	84.0	82.3
	A	1-P-17	834	0	.37484	.37621	163.203	64.255		
				3,565	.36961	.37602	163.170	64.245	88.5	86.8

Table No. B-5, continued.

Surface Treatment and Degree of Fretting	Testing Condition (See Note)	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Medially Fretted	B	1-C-25	722	0	.37443	.37537	164,327	63.233		
				3,200	.36792	.37823	164.284	63.197	94.1	92.4
	B	1-N-10	831	0	.37526	.37612	161.920	64.265		
				5,000	.37106	.37760	161.888	64.239	92.1	90.5
	B	1-N-5	801	0	.37484	.37540	162.580	64.325		
				4,500	.36905	.37768	162.536	64.287	92.2	90.5
	B	1-K-19	811	0	.37510	.37580	163.846	64.417		
				5,000	.37033	.37769	163.805	64.381	91.9	90.2
	B	1-N-15	830	0	.37500	.37598	163.277	64.295		
				3,840	.37029	.37949	163.239	64.246	92.3	90.6
	B	1-D-2	827	0	.37513	.37658	162.922	63.916		
				5,500	.36842	.37860	162.875	63.879	79.5	77.9
Severely Shot-Peened Medially Fretted	A	1-K-6	624	0	.37409	.37488	163.516	62.070		
				1,000	.36972	.37562	163.495	62.055	84.5	82.8
	B	1-H-17	805	500	.37514	.37669	162.394	63.850		
				4,500	.36736	.37862	162.330	63.817	80.1	78.4
	B	1-P-22	715	0	.37475	.37596	163.615	63.409		
				1,500	.37031	.37694	163.591	63.398	83.2	81.6
	B	1-P-20	845	0	.37486	.37652	161.560	63.847		
				3,500	.36449	.38332	161.395	63.805	89.9	88.2

Table No. B-5, continued.

Surface Treatment and Degree of Fretting	Testing Condition (See Note)	Specimen No.	Shoe No.	N_{fr} $\times 10^{-3}$	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress $\times 10^{-3}$, psi	Endurance Limit, $\times 10^{-3}$, psi
Severely	A	1-F-5	653	0	.37348	.37508	162.806	62.112		
Shot-Peened				1,940	.36491	.37487	162.778	62.098	93.3	91.6
Medially	A	1-J-7	706	0	.37448	.37594	162.680	63.244		
Fretted				1,909	.37071	.37605	162.658	63.233	88.9	87.3
	A	1-P-19	846	0	.37425	.37523	163.092	64.051		
				3,000	.37238	.37464	163.084	64.046	88.0	86.3
Severely	A	1-P-23	836	0	.37448	.37578	162.860	64.431		
Shot-Peened				3,100	.37209	.37523	162.849	64.427	89.4	87.7
Medially	A	1-P-24	663	0	.37408	.37544	163.717	62.115		
Fretted				2,846	.36779	.37693	163.684	62.084	94.2	92.5
	A	1-P-3	850	0	.37399	.37534	163.150	63.961		
				3,103	.37233	.37513	163.139	63.960	89.6	87.9
	A	1-P-18	815	0	.37434	.37584	162.727	63.821		
				1,180	.37091	.37592	162.709	63.815	80.7	78.9
	A	1-I-4	833	0	.37463	.37576	162.335	63.853		
				3,000	.37282	.37458	162.325	63.850	94.0	92.4
Severely	B	1-N-9	741	0	.37452	.37598	162.837	63.163		
Shot-Peened				5,214	.37128	.37681	162.824	63.153	93.8	92.1
Mildly	B	1-N-20	782	0	.37642	.37743	162.056	63.418		
Fretted				3,500	.37384	.37771	162.043	63.411	93.6	91.9
	B	1-N-14	868	0	.37393	.37471	164.021	64.387		
				7,300	.36936	.37613	163.987	64.363	95.2	93.5
	B	1-B-3	486	0	.37540	.37609	163.5210	62.5280		
				5,500	.37259	.37638	163.4970	62.5525	89.8	88.1

Table No. B-5, continued.

Surface Treatment and Degree of Fretting	Testing Condition (See Note)	Specimen No.	Shoe No.	N_{fr} x 10^{-3}	Ave. Specimen Diameter	Ave. Shoe Diameter	Specimen Weight, Grams	Shoe Weight, Grams	Prot Failure Stress x 10^{-3}, psi	Endurance Limit, x 10^{-3}, psi
Severely Shot-Peened Mildly Fretted	B	1-H-12	604	500	.37361	.37556	163.7595	62.4160		
				2,500	.37133	.37615	163.7432	62.4185	89.8	88.1
Severely Shot-Peened Mildly Fretted	A	1-N-12	829	0	.37492	.37591	162.224	63.705		
				5,050	.37450	.37552	162.220	63.703	85.5	83.9
	A	1-N-13	819	0	.37430	.37542	164.215	64.032		
				19,008	.36897	.37838	164.175	64.008	93.5	91.8
	A	1-N-18	844	0	.37573	.37608	163.824	64.185		
				30,000	.37421	.37627	163.811	64.177	92.9	91.3
	A	1-N-19	810	0	.37469	.37538	162.572	64.702		
				6,478	.37193	.37678	162.559	63.687	95.0	93.4
	A	1-G-26	847	0	.37446	.37585	162.212	64.447		
				3,000	.37413	.37531	162.211	64.446	——	——

Table B-6. Statistical Definition of Relationship Between Prot Rate and Failure Stress for Polished, Non-fretted Ti 140-A Titanium Specimens from Second Heat Using Prot Rates of $\alpha = 0.0025$, $\alpha = 0.01$, $\alpha = 0.04$, and $\alpha = 0.09$ psi per cycle.

α	Spec. No.	S_α x 10^{-3}
.0025	1-H-13	77.4
.0025	1-G-10	83.8
.0025	1-E-22	89.7
.0025	1-E-13	82.3
.0025	1-E-10	95.3
.0025	1-E-14	90.1
.0025	1-E-5	89.4
.0025	1-E-12	88.4
.0025	1-E-9	79.7
.0025	1-E-19	81.1
.0025	1-E-11	90.1
.0025	1-E-4	89.0
.0025	1-E-6	93.9
.0025	1-G-11	85.8
.0025	1-G-21	81.5
.01	1-A-1	87.4
.01	1-A-2	84.0
.01	1-A-3	81.5
.01	1-A-4	83.2
.01	1-A-5	87.3
.01	1-A-6	83.4
.01	1-A-7	85.5
.01	1-A-8	83.5
.01	1-A-9	87.5
.01	1-A-10	80.6
.01	1-A-11	86.2
.01	1-A-12	85.6
.01	1-A-13	87.5
.01	1-A-14	84.2
.01	1-A-15	85.0
.04	1-G-6	83.8
.04	1-G-12	86.2
.04	1-G-13	85.8
.04	1-G-16	87.9
.04	1-G-17	82.7

Table B-6, continued.

α	Spec. No.	S_α x 10^{-3}
.04	1-G-18	88.1
.04	1-H-3	85.8
.04	1-H-4	84.0
.04	1-H-9	85.4
.04	1-H-11	86.4
.04	1-H-15	84.6
.04	1-H-16	86.4
.04	1-H-19	83.4
.04	1-H-24	83.9
.04	1-H-23	84.4
.09	1-G-3	88.5
.09	1-G-4	89.6
.09	1-G-5	90.3
.09	1-G-7	88.4
.09	1-G-8	86.8
.09	1-G-9	86.4
.09	1-G-14	88.7
.09	1-G-15	89.4
.09	1-G-22	87.1
.09	1-G-23	85.8
.09	1-H-1	88.2
.09	1-H-2	87.2
.09	1-H-5	90.8
.09	1-H-10	91.0
.09	1-H-14	89.7

B-7. "Up and Down" Test for Verification of Prot Endurance Limit of Ti-140-A Titanium Specimens.

Spec. No.	Spec. Sequence	Failure Stress, psi	Run out Stress, psi
1-K-18	1		75,000
1-J-4	2		79,000
1-K-11	3	83,000	
1-K-17	4		79,000
1-K-20	5	83,000	
1-K-1	6		79,000
1-M-8	7		83,000
1-M-1	8	87,000	
1-K-8	9	83,000	
1-M-12	10		79,000
1-M-7	11		83,000
1-K-21	12	87,000	
1-P-10	13		83,000
1-P-14	14	87,000	
1-P-16	15		83,000
1-P-6	16	87,000	
1-P-12	17	83,000	
1-P-13	18		79,000
1-N-17	19		83,000
1-N-21	20	87,000	

Table B-8. Statistical Definition of Endurance Limit for Polished, Non-fretted Ti-140-A Titanium Specimens from First Heat of Material.
Prot Rate = 0.01 psi per cycle.

Spec. No.	S_{α} x 10^{-3}	E x 10^{-3} (Approx.)
A-11	78.4	69.9
A-4	80.9	72.4
A-9	77.2	68.7
A-10	80.1	71.6
A-8	76.0	67.5
A-12	81.1	72.6
A-6	78.4	69.9
A-17	74.5	66.0
A-13	73.7	65.2
A-7	78.2	69.7
A-15	81.1	72.6
A-3	79.0	70.5
A-16	77.3	68.8
A-20	77.6	69.1
A-21	74.1	65.6
Q-15	83.9	75.4
Q-21	80.5	72.0
Q-27	85.0	76.5
Q-28	78.3	69.8
Q-30	82.3	73.8
Q-32	82.1	73.6
Q-33	83.8	75.3
Q-34	85.0	76.5
R-29	78.2	69.7
R-30	79.5	71.0
R-34	71.3	62.8
R-35	78.6	70.1
R-36	79.8	71.3
R-37	77.6	69.1
R-38	77.5	69.0

Table B-9. Statistical Definition of Endurance Limit for Polished, Non-fretted Ti-140-A Titanium Specimens from Second Heat of Material.
Prot Rate = 0.01 psi per cycle.

Spec. No.	S_{α} x 10^{-3}	E x 10^{-3} (Approx.)
1-A-1	87.4	78.9
1-A-2	84.0	75.5
1-A-3	81.5	73.0
1-A-4	83.2	74.7
1-A-5	87.3	78.8
1-A-6	83.4	74.9
1-A-7	85.5	77.0
1-A-8	83.5	75.0
1-A-9	87.5	79.0
1-A-10	80.6	72.1
1-A-11	86.2	77.7
1-A-12	85.6	77.1
1-A-13	87.5	79.0
1-A-14	84.2	75.7
1-A-15	85.0	76.5
1-E-21	92.4	83.9
1-E-8	88.0	79.5
1-E-20	90.5	82.0
1-E-16	85.7	77.2
1-E-2	94.9	86.4
1-E-3	80.7	72.2
1-E-7	91.7	83.2
1-D-22	82.3	73.8
1-H-21	81.9	73.4
1-G-2	84.3	75.8
1-I-2	83.8	75.3
1-D-18	84.2	75.7
1-D-20	79.7	71.2
1-F-6	88.6	80.1
1-J-21	92.3	83.8

Table B-10. Chemical and Physical Properties of Two Heats of Ti-140-A Titanium Alloy Specimen Material.

Heat No.	C	N	Fe	Cr	Mo	H_2	Yield psi x 10^{-3}	Tensile psi x 10^{-3}	Elong. %	Red. in Area %
First	.054	.023	2.01	1.95	1.74	---	119.5	132	16	24
Second	.027	.024	2.16	1.93	1.99	.004	130.1	140.2	24	46.4

All properties and compositions in the above table were supplied by the manufacturer and the results are certified by the Titanium Metals Corporation of America.

Table B-11. Statistical Definition of Endurance Limit for Polished, Non-fretted Ti-140-A Titanium Specimens from First Heat. Prot Rate = 0.01 psi per cycle.

Spec. No.	S_{∞} x 10^{-3}	E x 10^{-3} (Approx.)
Q-15	83.9	75.4
Q-21	80.5	72.0
Q-27	85.0	76.5
Q-28	78.3	69.8
Q-30	82.3	73.8
Q-32	82.1	73.6
Q-33	83.8	75.3
Q-34	85.0	76.5
R-29	78.2	69.7
R-30	79.5	71.0
R-34	71.3	62.8
R-35	78.6	70.1
R-36	79.8	71.3
R-37	77.6	69.1
R-38	77.5	69.0

Table B-12. Statistical Definition of Endurance Limit for Polished, Severely Fretted Ti-140-A Titanium Specimens from First Heat.

Prot Rate = 0.01 psi per cycle.
No. of Fretting Cycles = 100,000.
Fretting Speed = 4,000 cycles per min.
S_1 = 0 psi.

Spec. No.	S_α x 10^{-3}	E x 10^{-3} (Approx.)
Q-2	67.5	59.0
Q-3	25.2	16.7
Q-4	55.4	46.9
Q-5	70.0	61.5
Q-7	45.9	37.4
Q-9	19.0	10.5
Q-10	54.3	45.9
Q-11	76.8	68.3
Q-12	42.8	34.3
Q-13	43.2	34.7
Q-16	81.0	72.5
Q-17	51.4	42.9
Q-18	31.8	23.3
Q-20	56.5	48.0
Q-25	21.1	12.6

Table B-13. Statistical Definition of Endurance Limit for Severely Shot-Peened, Severely Fretted, Ti-140-A Titanium Specimens from First Heat.

Prot Rate = 0.01 psi per cycle.
Fretting Speed = 4000 cycles per min.
No. of Fretting Cycles = 100,000.
S_1 = 50,000 psi.

Spec. No.	S_α x 10^{-3}	E x 10^{-3} (Approx.)
R-8	88.4	79.9
R-14	89.0	80.5
R-16	88.1	79.6
R-18	86.4	77.9
R-19	89.9	81.4
R-23	87.4	78.9
R-24	89.9	81.4
R-26	88.3	79.8
R-27	87.5	79.0
R-25	89.2	80.7
R-28	89.6	81.1
R-31	84.6	76.1
R-33	85.9	77.4
R-21	83.0	74.5
R-26	87.4	78.9

Table B-14. Statistical Definition of Endurance Limit for Severely Cold-Rolled, Severely Fretted Ti-140-A Titanium Specimens from First Heat.

Prot Rate = 0.01 psi per cycle.
Fretting Speed = 4000 cycles per min.
No. of Fretting Cycles = 100,000
S_1 = 25,000 psi.

Spec. No.	S_α x 10^{-3}	E x 10^{-3} (Approx.)
R-1	87.7	79.2
R-3	88.4	79.9
R-4	90.1	81.6
R-5	88.4	79.9
R-7	89.9	81.4
R-9	88.3	79.8
R-10	88.3	79.8
R-11	87.5	79.0
R-12	87.7	79.2
R-15	89.1	80.6
R-17	87.3	78.8
R-22	87.9	79.4
R-2	88.7	80.2
R-6	88.6	80.1
R-13	86.5	78.0

Table B-15. Effects of Fretting Speed Variation on Endurance Limit of Ti-140-A Titanium Specimens Subjected to Severe Fretting Conditions.

Speed	Spec. No.	Prot Failure Stress, $S_\alpha \times 10^{-3}$ psi
7200	1-M-17	85.1
	1-L-4	78.0
	1-N-3	78.0
	1-M-16	72.5
	1-N-2	71.9
	1-M-13	71.6
	1-N-1	71.2
	1-L-14	69.4
	1-M-6	68.8
	1-M-14	65.6
	1-K-15	62.6
	1-M-15	60.4
	1-K-16	56.8
	1-M-9	51.2
	1-M-11	42.8
5500	1-L-12	83.0
	1-M-3	82.1
	1-M-2	81.3
	1-L-23	79.6
	1-L-11	79.5
	1-K-4	77.5
	1-K-5	75.9
	1-L-2	74.2
	1-M-4	73.7
	1-K-2	66.1
	1-L-13	57.7
	1-K-3	52.7
	1-K-7	26.9
	1-M-5	23.3
	1-L-24	18.4
4000	1-L-22	82.3
	1-L-6	71.3
	1-L-1	65.6
	1-L-16	48.6
	1-L-9	46.0

Table B-15, continued.

Speed	Spec. No.	Prot Failure Stress, $S_{\alpha} \times 10^{-3}$ psi
4000	1-L-29	45.8
	1-L-17	40.7
	1-L-7	31.0
	1-L-15	25.5
	1-L-19	20.3
	1-D-10	63.3
	1-D-5	51.7
	1-D-14	41.4
	1-D-16	56.4
	1-D-9	57.2
3000	1-D-24	56.1
	1-F-13	57.3
	1-F-18	44.7
	1-F-2	31.1
	1-F-10	59.7
	1-F-3	49.5
	1-F-14	60.3
	1-F-8	57.5
	1-F-7	82.3
	1-F-20	81.5
	1-F-16	80.2
	1-F-21	78.4
	1-F-12	67.8
	1-F-19	57.5
	1-F-15	41.1
1600	1-F-22	82.9
	1-J-1	34.9
	1-F-24	75.3
	1-F-23	52.7
	1-F-27	38.7
	1-F-30	77.5
	1-F-28	78.0
	1-F-32	51.8
	1-J-5	77.9
	1-J-2	84.5
	1-F-26	57.2
	1-J-3	39.0
	1-J-6	76.1
	1-F-31	57.2
	1-F-29	67.5

Table B-15, continued.

Speed	Spec. No.	Prot Failure Stress, $S_{\alpha} \times 10^{-3}$ psi
1000	1-J-16	84.9
	1-J-18	83.9
	1-J-14	83.9
	1-J-10	83.7
	1-J-8	47.8
750	1-L-3	80.9
	1-K-14	80.2
	1-K-12	79.0
	1-K-10	77.6
	1-K-9	62.5
500	1-J-9	86.7
	1-J-15	83.7
	1-J-19	82.0
	1-J-20	74.5
	1-D-17	72.6
100	1-B-6	83.5
	1-B-7	78.1
	1-B-25	81.6
	1-B-5	74.0
	1-D-3	78.1
	1-D-6	79.5
	1-D-4	84.5
	1-D-13	81.2
	1-D-12	78.5
	1-D-1	78.5
	1-D-8	78.2
	1-D-7	77.6
	1-D-11	85.4
	1-D-23	79.4
	1-D-21	79.7

Table B-16. "Up and Down" Endurance Data for 0.187 Gauge Tempered Wire Specimens.

Spec. Sequence	Failure Stress, psi	Runout Stress, psi
1		70,000
2	75,000	
3		70,000
4	75,000	
5		70,000
6	75,000	
7		70,000
8	75,000	
9		70,000
10	75,000	
11	70,000	
12		65,000
13	70,000	
14		65,000
15	70,000	
16		65,000
17	70,000	
18		65,000
19	70,000	
20		65,000
21	70,000	

Table B-17. Macroscopic Fretting Specimen Data

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture			Sketch of Fretted Area
						β	W/L	σ	
A7-2	103	P	[M] N(1×10^6)	1×10^6	77,996	--	--	70	
A6-6	111				72,308	90	1/4	90	
A10-13	122				82,623	90	1/4	90	
A7-10	127				69,659	--	--	85	
A6-7	130				71,180	--	--	90	
A6-19	158	P	[M] N(5×10^6)	5×10^6	85,268	--	--	80	
A8-11	115				81,938	90	1/4	80	
A3-6	112				76,863	--	--	75	
A9-16	169				66,311	90	1/4	90	
A8-2	199				80,774	--	--	75	

Table E-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
A7-3	145	P	[M] $N(1 \times 10^7)$	1×10^7	48,444	0	1/3	85	
A8-7	93				57,476	90	1/3	90	
A5-4	83				76,641	--	--	75	
A8-6	179				75,034	--	--	70	
A6-1	187				85,229	90	1/4	90	
A7-11	114	P	[Me] $N(1.5 \times 10^4)$	1.5×10^4	69,957	85	1/4	80	
A5-14	124				63,965	0	1/2	90	
A6-11	61				71,733	--	--	80	
A6-4	150				78,560	--	--	80	
A8-3	123				78,993	--	--	90	
A8-4	155	P	[Me] $N(1 \times 10^6)$	1×10^6	28,920	90	2/3	90	
A8-10	147				34,275	0	2/3	90	
A7-13	146				57,065	90	2/3	90	
A7-4	76				26,743	90	1/2	90	
A5-12	109				47,009	90	1/2	90	

Table B-17, continued.

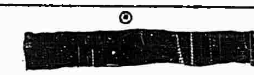
Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	$S_{\propto}$	Fracture β	Fracture W/L	Fracture ϑ	Sketch of Fretted Area
A8-1	132	P	[Me] N(5 x 10^6)	5 x 10^6	84,556	--	--	90	
A7-9	143				63,743	90	1/5	90	
A10-9	142				74,196	90	1/5	90	
A5-13	197				79,506	90	1/6	80	
A7-12	195				59,404	90	1/5	90	
A4-6	19	P	[S] N(1.5 x 10^4)	1.5 x 10^4	69,620	90	2/5	85	
A6-15	15				70,423	--	--	90	
A8-5	67				70,819	85	1/5	85	
A7-1	14				75,699	--	--	90	
A3-7	163				75,242	--	--	80	
A3-3	55	P	[S] N(1 x 10^6)	1 x 10^6	82,720	90	1/5	90	
A4-7	60				68,912	90	1/5	90	
A3-4	57				86,416	90	1/5	90	
A3-14	24				61,407	90	1/4	85	
A4-3	65				53,295	90	1/5	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture α	Sketch of Fretted Area
A4-10	58	P	[S] N(5 x 10^6)	5 x 10^6	80,239	90	1/5	90	
A5-7	106				83,934	--	--	80	
A7-15	181				78,173	--	--	90	
A5-11	192				54,346	90	1/5	90	
A6-16	196				53,029	90	1/6	90	
A3-1B	75	P	M	1 x 10^5	70,140	--	--	80	
A5-17	77				82,912	85	1/4	90	
A5-3	92				82,648	--	--	80	
A4-14	110				76,258	--	--	90	
A6-10	102				76,471	--	--	80	
A11-12	288	P	M	1 x 10^5	83,073	--	--	90	
A11-14	275				73,843	--	--	90	
A10-6	290				76,583	60	1/3	90	
A11-4	294				73,515	90	1/3	90	
A11-13	277				75,084	--	--	80	

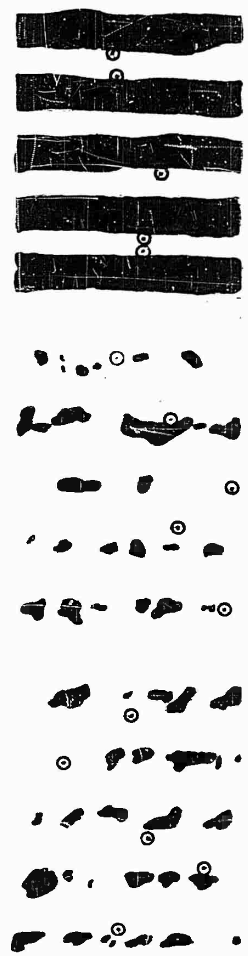


Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_∞	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
A10-2	262	P	M	1×10^5	79,441	--	--	80	
A11-10	255				83,090	--	--	70	
A11-16	263				72,481	--	--	85	
A10-7	242				77,762	--	--	90	
A9-17	421				75,929	--	--	80	
A6-14	131	P	Me	1×10^5	74,511	--	--	85	
A10-14	80				74,613	90	1/2	80	
A5-6	129				68,823	90	1/2	75	
A11-7	113				84,772	--	--	85	
A10-5	140				59,993	0	1/2	90	
A11-3	223	P	Me	1×10^5	73,615	--	--	85	
A10-4	225				72,773	--	--	75	
A9-11	219				73,799	--	--	90	
A11-6	239				69,272	90	1/4	90	
A9-5	217				72,787	--	--	85	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
A9-7	240	P	Me	1×10^5	74,349	40	1/2	90	
A9-6	246				69,944	--	--	85	
A9-15	230				63,836	90	2/3	90	
A6-9	212				71,856	90	1/2	80	
A9-2	237				72,763	--	--	80	
A3-1	71	P	S	1×10^5	64,702	--	--	85	
A3-15	72				51,965	90	1/4	90	
A4-15	10				65,814	--	--	99	
A4-12	66				67,567	30	1/2	85	
A3-9	70				61,502	30	1/3	90	
A3-16	477	P	S	1×10^5	72,043	75	1/3	85	
A9-3	385				72,273	90	1/3	90	
A11-1	291				68,559	90	1/2	90	
A10-1	266				71,866	--	--	75	
A10-10	270				67,105	90	5/6	75	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	$S_{\propto}$	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
A11-15	293	P	S	1×10^5	71,967	90	1/2	90	
A9-12	400				59,930	90	3/4	90	
A10-16	267				70,300	--	--	80	
A11-2	279				79,937	--	--	80	
A11-11	321				69,821	90	2/5	90	
G-33	137	P	[M] $N(1.5 \times 10^4)$	1.5×10^4	73,802	--	1/1	90	
H-3	159				77,489	--	--	90	
H-6	139				77,343	--	--	80	
H-1	171				77,072	--	--	80	
H-7	149				76,431	0	1/2	90	
I-10	210	P	[M] $N(5 \times 10^5)$	5×10^5	81,003	90	1/2	90	
I-4	194				76,983	90	1/3	85	
I-7	222				79,145	--	--	90	
I-9	251				75,603	90	2/5	90	
I-8	249				79,853	--	--	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
G-19	105	P	[M] N(1×10^6)	1×10^6	78,131	--	--	90	
G-18	98				52,783	90	1/3	90	
G-13	56				78,496	90	1/2	85	
G-16	51				75,994	90	4/5	85	
G-12	94				75,490	90	1/3	90	
I-24	209	P	[M] N(2.5×10^6)	2.5×10^6	76,299	90	1/4	90	
I-34	216				79,325	90	1/3	90	
I-23	228				77,900	90	1/7	90	
I-21	256				77,012	90	1/6	90	
I-22	254				76,255	--	--	90	
H-8	180	P	[M] N(5×10^6)	5×10^6	76,818	--	--	85	
G-22	119				59,113	90	2/3	90	
H-10	133				78,137	--	--	85	
G-30	134				77,756	90	1/4	90	
G-24	125				60,112	--	--	90	

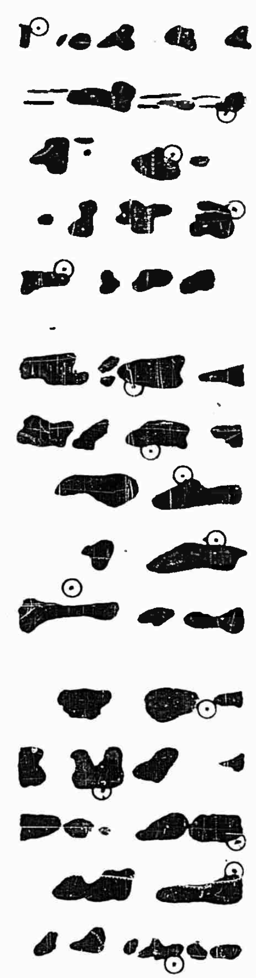


Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
G-27	126	P	[M] $N(1 \times 10^7)$	1×10^7	44,328	--	--	90	
G-29	160				36,557	0	3/4	90	
G-2	120				40,337	-0	3/4	90	
G-23	141				75,048	--	1/1	90	
G-11	100	P	[Me] $N(1.5 \times 10^4)$	1.5×10^4	76,997	90	1/4	90	
G-5	136				76,761	--	--	85	
G-9	154				75,734	0	2/3	90	
G-32	152				77,919	0	1/2	90	
G-21	166				76,477	--	--	90	
H-2	173	P	[Me] $N(5 \times 10^4)$	5×10^4	78,876	--	--	90	
H-26	184				77,279	--	--	90	
H-25	170				63,391	90	1/2	90	
H-27	185				78,158	45	1/3	90	
H-23	177				66,191	--	1/1	85	

Table B-1[illegible], continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
H-24	153	P	[Me] $N(5 \times 10^5)$	5×10^5	67,662	90	2/3	90	
H-21	138				69,984	90	1/4	90	
I-2	206				54,994	90	1/2	90	
H-29	190				78,725	90	1/5	90	
H-1	247				77,117	90	1/3	90	
I-11	227	P	[Me] $N(5 \times 10^5)$	5×10^5	61,993	90	1/5	90	
G-15	161	P	[Me] $N(1 \times 10^6)$	1×10^6	70,855	0	1/2	90	
G-4	157				37,535	90	1/3	90	
F-16	118				72,387	90	1/2	90	
H-13	178				76,878	90	1/4	90	
H-19	175	P	[Me] $N(1 \times 10^6)$	1×10^6	29,731	--	1/1	90	
I-15	232	P	[Me] $N(5 \times 10^6)$	5×10^6	79,767	90	1/6	90	
I-12	229				54,760	90	1/6	90	
I-13	248				76,804	--	--	90	
I-5	250				67,609	90	1/8	90	

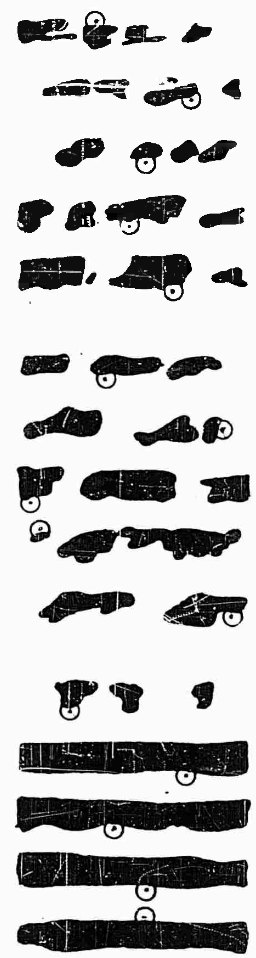


Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
H-12	182	P	[Me] N(5 x 10^6)	5 x 10^6	79,493	90	1/4	90	
H-269	202		[S] N(2 x 10^3)	2 x 10^3	79,264	90	1/3	90	
I-3	183				77,251	45	1/2	85	
H-28	186				75,188	90	1/5	90	
H-249	203				81,086	45	1/2	90	
H-239	204	P	[S] N(2 x 10^3)	2 x 10^3	73,435	0	1/2	90	
F-9	22	P	[S] N(1.5 x 10^4)	1.5 x 10^4	78,650	60	1/3	85	
F-15	63				36,661	90	1/2	90	
F-12	54				79,127	0	1/4	90	
F-11	20				37,188	90	1/3	90	
F-21	81	P	[S] N(1.5 x 10^4)	1.5 x 10^4	46,700	90	1/4	90	
H-11	174	P	[S] N(5 x 10^4)	5 x 10^4	31,455	--	1/1	90	
H-18	167				43,225	90	1/3	90	
H-15	135				43,883	0	1/2	90	
H-17	117				73,535	--	1/1	90	

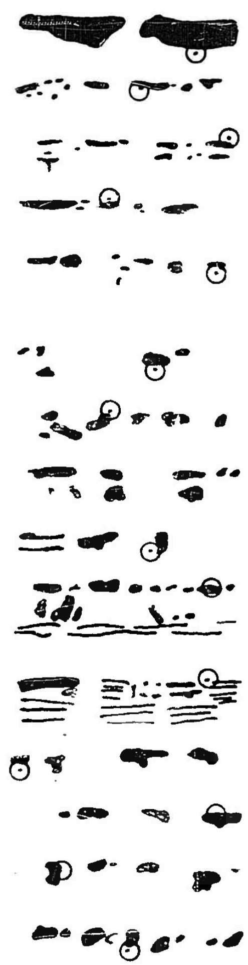


Table 3-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
H-16	176	P	[S] N(5 x 10^4)	5 x 10^4	49,574	90	1/3	90	
F-8	50	P	[S] N(1.5 x 10^5)	1.5 x 10^5	27,516	90	4/5	90	
H-4	121	P	[S] N(2.5 x 10^5)	2.5 x 10^5	22,287	90	1/2	90	
H-20	.172				17,856	90	1/4	90	
H-22	205				69,512	90	1/2	90	
H-259	168	P	[S] N(2.5 x 10^5)	2.5 x 10^5	70,533	90	1/8	90	
H-279	191				26,485	90	2/3	90	
F-7	1	P	[S] N(5 x 10^5)	5 x 10^5	54,091	90	1/4	90	
I-20	234				55,674	90	1/2	90	
I-14	193				23,428	--	1/1	90	
I-18	200	P	[S] N(5 x 10^5)	5 x 10^5	36,519	90	4/5	90	
I-16	224				43,054	90	1/6	90	
G-1	104	P	M	1 x 10^5	77,027	--	--	90	
F-13	96				76,091	--	--	90	
F-10	97				78,100	--	--	90	

Table B-17, continued.

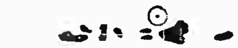
Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
G-6	108	P	M	1×10^5	75,869	90	1/2	90	
F-17	89				78,682	--	--	85	
J-6	308				79,288	--	--	85	
J-22	337				83,820	85	1/3	85	
J-17	339				79,620	--	--	90	
J-29	324	P	M	1×10^5	84,719	90	1/4	90	
J-2	323				85,725	--	--	90	
J-18	310				87,824	--	--	90	
J-14	345				83,639	90	1/5	90	
J-15	320				79,325	--	--	85	
J-5	305	P	M	1×10^5	83,898	0	2/3	90	
J-8	319				82,205	--	--	90	
G-25	53	P	Ma	1×10^5	54,326	90	1/2	90	
G-3	164				49,325	--	1/1	90	
G-31	107				48,676	90	2/3	90	

Table 3-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture			Sketch of Fretted Area
						β	W/L	σ	
G-20	151	P	Me	1×10^5	67,619	--	1/1	90	
G-8	116				74,146	90	4/5	90	
I-30	211				34,897	90	1/2	90	
I-29	231				62,113	0	1/3	90	
I-26	213				36,392	90	1/2	90	
I-32	208	P	Ms	1×10^5	49,117	90	1/3	90	
I-31	233				37,498	90	1/2	90	
I-27	214				58,675	90	4/7	90	
I-35	220				62,452	75	2/3	90	
I-33	226				76,060	0	1/2	90	
J-25	318	P	Ms	1×10^5	79,675	60	1/2	90	
J-21	336				80,882	--	--	80	
D-28	17	P	S	1×10^5	61,654	0	1/3	90	
D-30	52				31,746	90	1/3	90	
F-24	74				25,560	90	1/5	90	

Table 3-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture γ	Sketch of Fretted Area
F-18	62	P	S	1×10^5	35,846	90	1/4	90	
F-22	59				69,213	90	1/3	90	
F-14	86				43,822	90	1/4	90	
F-19	78				39,717	90	1/4	90	
D-29	88				21,326	--	1/1	90	
J-1	283	P	S	1×10^5	13,926	90	1/3	90	
J-4	297				21,659	90	1/4	90	
J-3	292				25,130	90	1/2	90	
J-26	348				58,117	80	1/4	90	
J-34	355				63,442	--	1/1	90	
J-12	313	P	S	1×10^5	30,021	--	1/1	90	
J-9	304				61,422	80	1/2	90	
J-11	299				20,293	90	2/3	90	
J-20	312				30,754	90	1/3	90	
J-30	325				19,305	90	1/7	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{∞}	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
Q-7	553	P	S	1×10^5	45,921	90	1/4	90	
Q-5	567				70,039	90	1/3	90	
Q-4	506				55,394	90	1/2	90	
Q-3	522				25,199	90	1/2	90	
Q-2	512				67,481	80	1/2	90	
Q-12	490	P	S	1×10^5	42,760	90	1/4	90	
Q-11	555				76,837	90	1/3	90	
Q-10	603				54,348	60	1/2	90	
Q-25	516				21,050	90	1/5	90	
Q-20	533				56,490	90	1/2	90	
Q-18	496	P	S	1×10^5	31,750	—	1/1	90	
Q-17	595				51,406	90	1/2	90	
Q-16	578				80,955	90	1/3	90	
Q-13	539				43,217	0	2/3	90	
1-L-17	758				40,741	90	1/4	90	

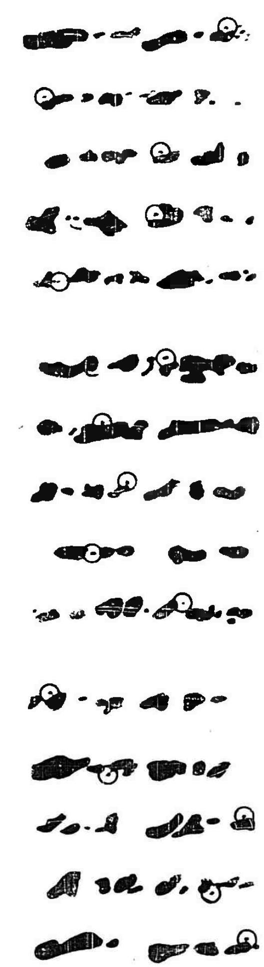


Table D-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture γ	Sketch of Fretted Area
1-L-16	716	P	S	1×10^5	48,596	90	1/11	90	
1-L-15	790				25,507	90	1/4	90	
1-L-22	795				81,280	90	1/5	85	
1-L-1	777				65,564	90	1/3	90	
1-D-9	509				57,232	—	1/1	90	
1-D-10	590	P	S	1×10^5	63,345	90	1/8	90	
1-D-14	699				41,385	—	1/1	90	
1-D-5	616				51,747	90	2/3	90	
1-D-16	545				56,409	90	1/3	90	
1-L-19	774				20,321	90	1/7	90	
1-L-6	769	P	S	1×10^5	71,261	90	1/5	90	
1-L-9	781				45,993	90	1/7	90	
1-L-29	768				45,763	90	1/6	90	
1-L-7	779				31,019	90	1/7	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
1-D-21	665	P	[S] S(100)	1×10^5	79,721	90	1/7	90	
1-B-6	489				83,491	90	1/9	85	
1-B-5	576				74,019	90	1/7	90	
1-D-11	641				85,404	90	1/6	85	
1-D-3	658				78,066	90	1/3	90	
1-D-6	626	P	[S] S(100)	1×10^5	79,496	90	1/6	90	
1-D-4	675				84,474	90	1/6	90	
1-D-13	697				81,244	90	1/7	85	
1-D-12	612				78,454	90	1/7	85	
1-D-1	630				78,404	90	1/5	85	
1-D-8	649	P	[S] S(100)	1×10^5	78,158	90	1/4	90	
1-D-7	627				77,608	90	1/4	90	
1-B-25	606				81,572	90	1/6	90	
1-B-7	521				78,080	90	1/5	90	
1-D-23	683				79,411	--	--	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
1=J=15	787	P	[S] S(500)	1 x 10^5	83,722	90	1/8	85	
1-J-9	698				86,667	90	1/5	90	
1-J-19	775				82,023	90	1/9	90	
1-D-17	772				72,601	90	1/12	90	
1-J-20	747				74,524	90	1/8	90	
1-K-14	783	P	[S] S(750)	1 x 10^5	80,226	--	--	--	
1-K-12	778				79,024	90	1/8	90	
1-K-10	713				77,568	90	1/6	90	
1-L-3	770				80,914	90	1/15	90	
1-K-9	717				62,549	90	1/3	90	
1-J-10	703	P	[S] S(1000)	1 x 10^5	83,721	90	1/6	90	
1-J-14	719				83,946	90	2/7	90	
1-J-18	714				83,946	90	1/6	85	
1-J-8	712				47,859	90	1/3	90	
1-J-16	725				84,953	90	1/8	90	

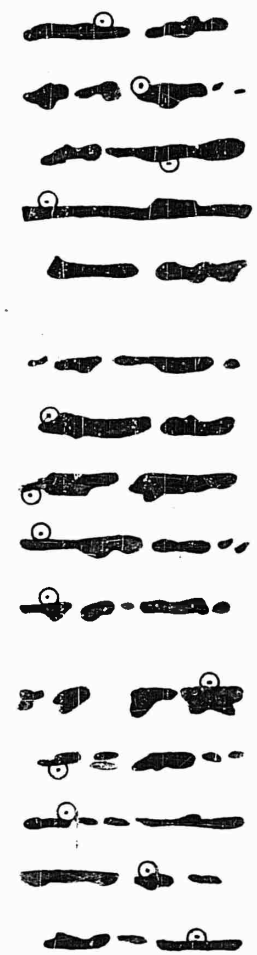
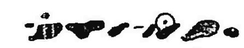
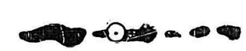


Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
1-F-22	565	P	[S] S(1600)	1×10^5	82,868	90	1/5	90	
1-F-23	691				52,673	80	1/2	90	
1-J-1	617				34,917	90	1/2	90	
1-F-24	696				75,263	90	2/5	90	
1-F-27	485				38,715	90	1/2	90	
1-F-30	562	P	S S(1600)	1×10^5	77,549	90	1/3	85	
1-F-28	459				77,952	90	1/6	90	
1-F-32	596				51,764	90	2/5	90	
1-J-5	552				77,947	90	1/8	90	
1-J-2	602				84,523	90	1/6	90	
1-F-26	507	P	[S] S(1600)	1×10^5	57,209	90	1/7	90	
1-F-29	548				67,507	90	1/3	90	
1-F-31	570				57,249	90	2/3	90	
1-J-3	679				39,040	90	2/3	90	
1-J-6	729				76,060	90	2/7	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture φ	Sketch of Fretted Area
1-F-19	598	P	[S] S(3000)	1×10^5	57,491	90	1/2	90	
1-F-12	664				67,767	90	1/3	90	
1-F-21	688				78,424	90	1/3	90	
1-F-16	677				80,188	90	1/6	90	
1-F-20	625				81,538	90	1/8	90	
1-F-7	582	P	[S] S(3000)	1×10^5	82,346	90	1/5	85	
1-F-8	635				57,502	90	1/3	90	
1-F-14	693				60,288	90	1/9	90	
1-F-3	629				49,515	90	1/4	90	
1-F-10	694				59,704	--	1/1	90	
1-F-2	692	P	[S] S(3000)	1×10^5	31,074	90	2/3	90	
1-F-18	654				44,695	90	1/3	90	
1-F-13	531				57,339	90	1/4	90	
1-D-24	583				56,071	90	2/5	90	
1-F-15	644				41,125	90	1/2	90	

T-ble ?-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
1-K-5	723	P	[S] S(5500)	1×10^5	75,932	90	1/6	90	
1-L-2	761				74,296	90	1/2	90	
1-L-24	731				18,432	90	1/8	90	
1-M-3	718				82,109	90	1/6	90	
1-M-5	793				23,265	90	1/7	90	
1-L-23	797	P	[S] S(5500)	1×10^5	79,581	90	2/5	90	
1-L-13	733				57,729	90	1/2	90	
1-K-3	734				52,724	85	1/2	90	
1-K-4	776				77,495	90	1/10	90	
1-K-2	732				66,146	90	1/3	90	
1-K-7	727	P	[S] S(5500)	1×10^5	26,864	90	4/5	90	
1-L-12	736				82,962	90	1/2	80	
1-L-11	721				79,549	90	1/5	85	
1-M-4	784				73,694	90	1/6	90	
1-M-2	743				81,265	90	1/2	85	

Table B-17, continued.

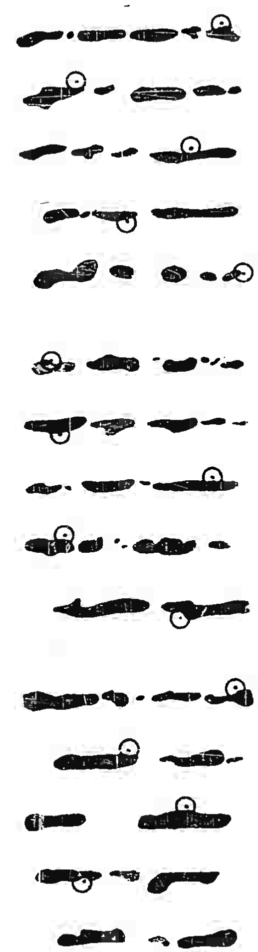
Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
1-K-16	745	P	[S] S(7200)	1×10^5	56,811	90	1/5	90	
1-L-4	792				77,983	90	1/7	90	
1-M-14	720				65,593	90	1/12	90	
1-L-14	742				69,393	90	1/5	90	
1-K-15	767				62,561	90	1/2	90	
1-M-6	796	P	[S] S(7200)	1×10^5	68,773	90	1/3	90	
1-M-13	709				71,613	90	1/7	90	
1-N-2	708				71,886	90	1/10	90	
1-M-11	702				42,785	90	1/3	90	
1-M-9	737				51,252	90	1/9	90	
1-M-15	707	P	[S] S(7200)	1×10^5	60,442	90	1/7	90	
1-N-1	753				71,277	90	1/8	90	
1-N-3	710				78,013	90	1/8	90	
1-M-16	700				72,515	90	1/2	90	
1-M-17	744				85,107	--	--	--	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{∞}	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
I-C-3	613	P	Special	1×10^5	77,776	0	1/3	90	
L-C-5	628				77,955	90	1/2	90	
I-C-15	647				65,943	90	1/2	90	
I-C-14	662				62,608	90	1/5	90	
I-C-18	650				79,457	90	1/2	90	
I-A-19	554	P	Special	1×10^5	21,972	90	1/2	90	
I-C-22	605				13,014	90	2/5	90	
I-C-10	614				76,654	90	1/4	90	
I-C-12	651				71,484	90	1/2	90	
I-C-2	610				43,115	90	1/4	90	
L-C-7	611	P	Special	1×10^5	23,337	90	1/5	90	
I-C-21	645				70,613	90	1/4	90	
I-C-9	634				62,135	--	---	90	
I-C-1	640				54,138	90	1/5	90	
I-C-16	673				21,355	90	1/4	90	

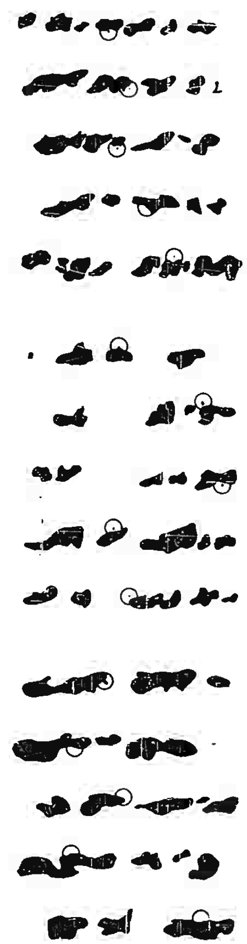


Table B-17, continued.

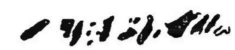
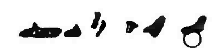
Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
I-C-4	487	P	Special	1×10^5	63,863	90	1/8	90	
I-C-17	575				42,455	90	1/4	90	
I-C-24	646				72,534	90	1/11	90	
I-B-2	484				35,237	90	1/3	90	
J-28	342	MSP	M	1×10^5	88,516	90	1/4	80	
J-10	346				84,693	--	---	80	
L-27	365				81,505	90	1/6	80	
J-13	306				83,771	0	1/2	90	
J-31	331				87,831	--	---	85	
K-25	381	MSP	M	1×10^5	85,089	--	---	90	
J-24	352				67,197	--	---	90	
J-23	330				88,212	--	---	85	
J-19	317				88,706	20	1/2	90	
I-25	273				86,000	--	---	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
K-31	872	MSP	M	1×10^5	86,771	--	---	90	
J-32	363				87,192	--	---	90	
J-27	358				83,382	--	---	90	
K-23	338				85,131	--	---	90	
J-33	268				84,468	--	---	90	
K-2	371	MSP	Me	1×10^5	82,095	--	---	90	
K-1	389				87,377	90	1/5	80	
K-21	384				84,723	90	1/4	85	
K-28	329				86,307	45	1/2	90	
K-33	343				84,802	--	---	90	
K-11	257	MSP	Me	1×10^5	86,626	90	2/3	85	
K-29	328				87,485	60	1/2	90	
K-32	300				81,118	--	---	90	
L-29	378				81,474	90	1/6	90	
K-5	307				88,172	--	---	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	$S_{\sim}$	Fracture β	Fracture W/L	Fracture α	Sketch of Fretted Area
K-7	32[illegible]	MSP	Me	1×10^5	84,548	90	1/4	90	
K-26	359				81,427	90	1/3	80	
K-4	282				83,981	--	---	90	
K-6	364				86,660	90	1/4	90	
K-30	349				87,192	90	1/3	90	
K-8	360	MSP	S	1×10^5	89,448	90	1/5	80	
K-10	298				84,924	90	2/5	90	
K-13	303				80,155	90	1/5	85	
K-14	370				81,884	--	---	90	
K-15	316				83,641	0	3/4	90	
K-16	314	MSP	S	1×10^5	83,998	90	1/4	90	
K-17	264				82,256	--	---	90	
K-18	357				83,641	90	1/7	90	
K-19	373				83,870	90	1/10	90	
K-24	341				84,194	90	1/3	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
K-22	344	MSP	S	1×10^5	86,729	—	1/1	85	
K-20	356				85,653	90	1/2	90	
L-28	363				85,425	90	1/8	90	
I-N-9	741	SSP	[M] N(2.2×10^6)	2.2×10^6	91,616	--	—	90	
I-N-20	782		[M] N(3.5×10^6)	3.5×10^6	91,848	—	—	90	
I-N-14	868	SSP	[M] N(7.3×10^6)	7.3×10^6	92,064	90	1/6	90	
I-H-12	604		[M] N(3×10^6)	3×10^6	87,529	90	1/7	90	
I-B-3	486		[M] N(6×10^6)	6×10^6	89,834	90	1/11	85	
I-C-25	722	SSP	[Me] N(3.2×10^6)	3.2×10^6	89,182	90	1/6	90	
I-N-10	831		[Me] N(5×10^6)	5×10^6	89,189	90	1/6	90	
I-N-5	801	SSP	[Me] N(4.5×10^6)	4.5×10^6	89,233	90	1/5	90	
I-K-19	811		[Me] N(5.5×10^6)	5.5×10^6	87,057	90	1/5	90	
I-N-15	830		[Me] N(3.84×10^6)	3.84×10^6	89,130	90	1/6	90	
I-N-12	829	SSP	[M] N(5050×10^3)	5050×10^3	85,531	90	1/2	90	
I-N-13	819		[M] N(19×10^6)	19×10^6	93,490	90	1/7	85	

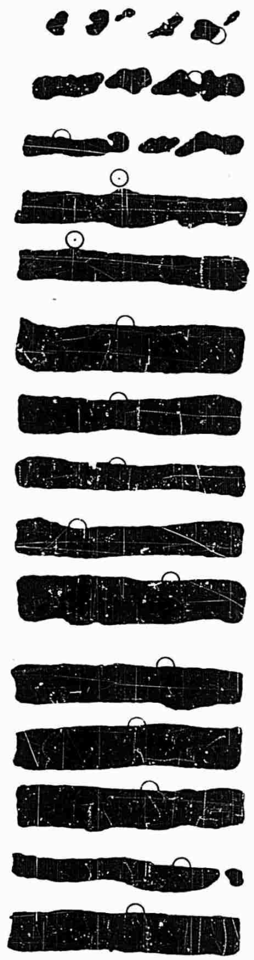


Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
I-N-18	844		$\boxed{M}$ N(3 x 10^7)	3 x 10^7	92,923	90	1/6	80	
I-N-19	810		$\boxed{M}$ N(6478 x 10^3)	6478 x 10^3	95,030	90	1/8	90	
I-G-26	847		$\boxed{M}$ N 3 x 10^6)	3 x 10^6	——	—	—	—	
I-F-5	653	SSP	$\boxed{Me}$ N(19 x 10^5)	19 x 10^5	93,291	90	1/11	85	
I-I-4	833		$\boxed{Me}$ N(3 x 10^6)	3 x 10^6	94,029	90	1/10	90	
I-P-19	846		$\boxed{Me}$ N(3 x 10^6)	3 x 10^6	87,986	90	1/11	90	
I-J-7	706		$\boxed{Me}$ N(19 x 10^5)	19 x 10^5	88,982	90	1/10	80	
I-P-3	850		$\boxed{Me}$ N(3 x 10^6)	3 x 10^6	98,564	90	1/10	90	
I-P-5	849	SSP	$\boxed{S}$ N(3 x 10^6)	3 x 10^6	86,897	90	1/10	85	
I-P-8	828		$\boxed{S}$ N(276 x 10^4)	276 x 10^4	85,098	90	1/7	90	
I-P-11	661		$\boxed{S}$ N(93 x 10^4)	93 x 10^4	83,950	90	1/10	85	
I-P-17	834		$\boxed{S}$ N(356 x 10^4)	356 x 10^4	88,542	90	1/7	85	
I-K-6	624		$\boxed{S}$ N(1 x 10^6)	1 x 10^6	84,473	90	1/11	90	
I-C-13	619	SSP	$\boxed{S}$ N(15 x 10^5)	15 x 10^5	88,884	90	1/7	85	
I-C-11	638		$\boxed{S}$ N(17.5 x 10^5)	17.5 x 10^5	85,001	90	1/6	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
L-C-6	686	SSP	[S] N(16 x 10^5)	16 x 10^5	75,568	—	—	—	
L-1	415	SSP	M	1 x 10^5	83,659	—	—	90	
L-2	315				85,709	90	1/10	90	
L-3	361				85,870	--	—	90	
L-4	334				83,820	90	1/2	90	
L-5	449	SSP	M	1 x 10^5	85,394	--	—	90	
L-6	311				81,197	--	—	90	
L-7	369				82,688	--	—	90	
L-8	272				83,333	90	1/3	90	
L-9	327				84,450	10	1/3	90	
L-10	426	SSP	M	1 x 10^5	83,043	90	1/2	90	
L-11	296				81,648	90	1/6	90	
L-12	432				83,317	90	1/4	90	
L-13	435				84,991	--	—	90	
L-14	367				81,640	--	—	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S α	Fracture β	Fracture l/L	Fracture σ	Sketch of Fretted Area
L-15	285	SSP	M	1×10^5	83,252	0	1/3	90	
L-16	265	SSP	Me	1×10^5	83,526	--	---	85	
L-17	368				83,188	--	---	90	
L-18	354				81,600	--	---	90	
L-19	442				83,091	--	---	90	
L-20	460	SSP	Me	1×10^5	84,079	--	---	90	
L-21	377				81,941	--	---	90	
L-22	387				85,073	--	---	90	
L-23	454				85,636	--	---	90	
L-24	380				83,673	--	---	85	
L-25	388	SSP	Me	1×10^5	83,608	90	1/4	90	
L-26	335				83,334	--	---	90	
N-1	392				80,124	--	---	90	
N-2	416				82,914	--	---	90	
N-3	466				83,300	--	---	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S α	Fracture β	Fracture W/L	Fracture σ	Sketch of Fretted Area
N-5	302	SSP	Me	1 x 10^5	82,994	---	---	90	
N-19	375	SSP	S	1 x 10^5	84,349	90	1/5	85	
N-4	457				84,942	90	1/4	90	
N-7	383				82,202	90	1/8	90	
N-6	418				81,411	--	----	90	
N-8	411	SSP	S	1 x 10^5	82,560	90	1/7	85	
N-9	397				83,172	0	2/3	90	
N-10	350				83,414	90	1/5	90	
N-11	438				81,609	--	---	90	
N-12	403				82,556	90	1/2	90	
N-13	422	SSP	S	1 x 10^5	81,776	90	1/2	90	
N-14	445				83,107	90	1/9	90	
N-15	440				83,623	60	3/4	90	
N-16	410				82,301	90	1/2	90	
N-17	424				83,639	--	---	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
N-18	458	SSP	S	1×10^5	86,007	90	1/7	90	
R-24	503				89,853	60	1/3	90	
R-23	550				87,417	90	1/3	90	
R-19	580				80,922	--	---	85	
R-18	494				86,384	--	---	85	
R-16	543	SSP	S	1×10^5	88,110	75	1/2	90	
R-14	537				88,975	60	1/3	90	
R-28	584				89,555	--	---	90	
R-25	599				89,165	--	---	90	
Q-26	542				87,427	--	---	90	
R-8	593	SSP	S	1×10^5	88,434	80	1/3	85	
R-21	569				83,042	--	---	90	
R-33	527				85,918	--	---	80	
R-26	515				88,252	90	1/4	90	
R-31	579				84,621	--	---	--	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{α}	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
O-20	441	MCR	M	1×10^5	83,339	10	2/3	90	
L-30	390				82,617	90	2/5	90	
N-20	462				67,717	90	1/4	90	
N-23	394				81,086	90	2/5	90	
N-26	431				82,346	—	---	90	
L-31	453	MCR	M	1×10^5	83,853	90	1/4	90	
N-21	399				79,797	90	1/4	80	
N-25	464				80,724	90	1/4	90	
N-29	326				85,686	0	2/3	85	
N-30	429				84,208	45	1/3	90	
N-31	433	MCR	M	1×10^5	82,015	0	1/3	90	
N-32	398				83,722	90	1/3	85	
N-33	436				83,236	45	1/4	90	
N-28	414				84,696	---	1/1	90	
N-34	430				85,636	--	---	85	

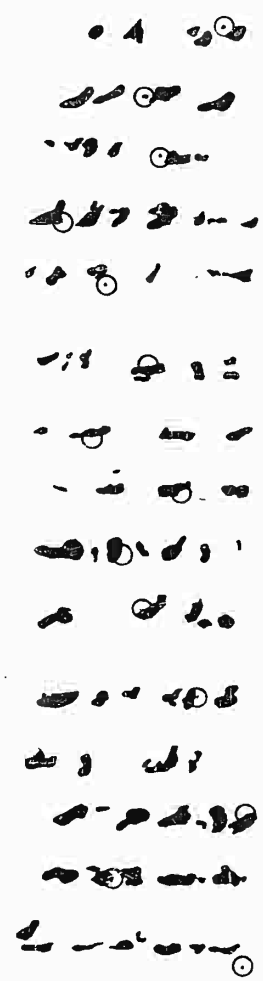


Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
O-5	473	MCR	Me	1×10^5	66,731	45	1/2	90	
O-24	434				69,447	90	2/3	90	
O-10	456				76,116	45	1/2	90	
O-29	451				73,398	90	1/3	90	
O-26	444				67,776	--	1/1	90	
O-30	374	MCR	Me	1×10^5	71,566	--	1/1	90	
O-11	465				87,446	60	1/3	90	
O-4	474				68,093	45	1/3	90	
O-32	405				84,270	90	2/3	85	
O-23	470				87,210	0	1/2	90	
O-33	391	MCR	Me	1×10^5	86,046	--	---	85	
O-21	439				71,733	--	1/1	90	
O-34	379				71,121	60	3/4	90	
O-22	382				90,134	90	1/3	80	
O-3	404				81,839	90	2/5	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
O-16	408	MCR	S	1×10^5	55, 469	0	1/3	90	
O-7	420				69,899	90	1/2	90	
O-17	427				64,983	90	1/4	90	
O-15	406				65,682	60	1/2	90	
O-9	419				67,778	---	1/1	90	
O-14	479	MCR	S	1×10^5	67,481	---	1/1	90	
O-18	481				76,433	90	1/4	90	
O-27	376				75,581	---	1/1	90	
O-28	396				67,908	90	1/3	90	
O-1	586				62,305	90	2/5	90	
O-2	547	MCR	S	1×10^5	72,755	0	1/2	90	
O-13	401				75,875	90	1/4	85	
O-8	463				65,541	90	1/2	90	
O-25	446				53,057	90	1/5	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
I-B-15	682	SCR	[Me] N(3 x 10^6)	3 x 10^6	91,475	--	---	--	
I-B-21	564		[Me] N(3035 x 10^3)	3035 x 10^3	89,781	90	1/7	90	
I-B-22	620		[Me] N(55 x 10^5)	55 x 10^5	89,975	90	1/7	90	
I-B-18	622		[Me] N(438 x 10^4)	438 x 10^4	87,801	--	---	--	
I-B-23	678		[Me] N(55 x 10^5)	55 x 10^5	90,309	--	---	--	
I-B-13	549	SCR	[S] N(35 x 10^5)	35 x 10^5	87,481	90	1/5	90	
I-B-12	676		[S] N(15 x 10^5)	15 x 10^5	90,326	90	1/6	85	
I-B-26	670		[S] N(25 x 10^5)	25 x 10^5	88,492	90	1/5	90	
I-H-20	608		[S] N(18 x 10^5)	18 x 10^5	89,136	90	1/5	90	
I-H-22	648		[S] N(15 x 10^5)	15 x 10^5	91,959	90	1/7	90	
L-32	450	SCR	M	1 x 10^5	90,466	45	1/4	90	
L-33	475				92,188	--	---	90	
P-2	468				94,507	45	1/2	90	
P-33	423				94,252	90	1/3	85	
P-21	333				90,997	75	1/6	90	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
P-14	428	SCR	M	1×10^5	94,851	--	---	90	
P-13	469				92,779	90	1/2	85	
P-10	409				93,501	--	---	90	
P-9	443				91,580	--	---	90	
P-8	413				93,294	--	---	90	
P-7	452	SCR	M	1×10^5	96,392	--	---	80	
P-6	425				96,899	--	---	90	
P-5	412				93,914	75	1/3	90	
P-4	471				94,673	0	1/2	80	
P-3	455				95,109	90	1/3	85	
P-23	502	SCR	Me	1×10^5	92,987	75	1/3	80	
P-20	492				93,762	90	1/3	90	
P-19	478				87,512	85	2/5	85	
P-22	476				93,005	0	1/3	85	
P-11	581				93,665	80	1/4	85	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_{∞}	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
P-17	557	SCR	Me	1×10^5	91,333	--	---	80	
P-30	540				94,942	--	1/1	90	
P-28	504				90,627	--	---	90	
P-27	417				90,944	90	1/4	90	
P-25	577				93,294	80	2/5	85	
P-31	393	SCR	Me	1×10^5	91,314	10	1/2	90	
P-24	493				88,036	60	2/5	80	
P-16	601				93,829	90	1/3	85	
P-15	499				91,563	90	1/2	85	
P-18	495				92,388	--	---	90	
Q-8	556	SCR	S	1×10^5	93,671	--	---	90	
P-34	541				90,361	90	2/3	90	
P-32	500				93,059	--	---	85	
P-12	518				92,329	80	1/3	90	
Q-1	520				93,605	90	1/2	80	

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture ϕ	Fracture W/L	Fracture θ
Q-29	600	SCR	S	1×10^5	93,447	0,	1/2	90
Q-24	560				93,398	--	---	85
P-26	563				91,157	90	1/4	85
Q-6	510				93,170	--	---	90
P-29	498				93,458	--	---	90
Q-22	517	SCR	S	1×10^5	93,184	90	1/2	90
Q-23	461				96,512	--	---	90
Q-31	501				92,514	--	---	90
Q-19	519				94,230	--	---	75
R-13	571				86,538	90	1/2	90
R-1	526	SCR	S	1×10^5	87,685	90	1/2	85
R-2	591				88,733	90	1/2	90
R-6	589				88,613	--	---	90
R-3	483				88,384	80	1/3	90
R-4	546				90,132	60	1/2	90

Sketch of Fretted Area

Table B-17, continued.

Spec. No.	Shoe No.	Surface Treatment	Fretting Treatment	N_{fr}	S_α	Fracture β	Fracture W/L	Fracture θ	Sketch of Fretted Area
R-5	508	SCR	S	1×10^5	88,401	90	1/4	90	
R-7	551				89,901	--	---	90	
R-9	523				88,322	90	1/4	85	
R-10	592				88,322	90	1/3	90	
R-11	530				87,461	85	2/5	90	
R-12	505	SCR	S	1×10^5	87,651	90	4/5	85	
R-15	488				89,055	90	1/2	90	
R-17	528				87,294	90	1/3	90	
R-22	514				87,863	90	1/4	90